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(54) **RADOME ASSEMBLY HAVING NODELESS CELLS**

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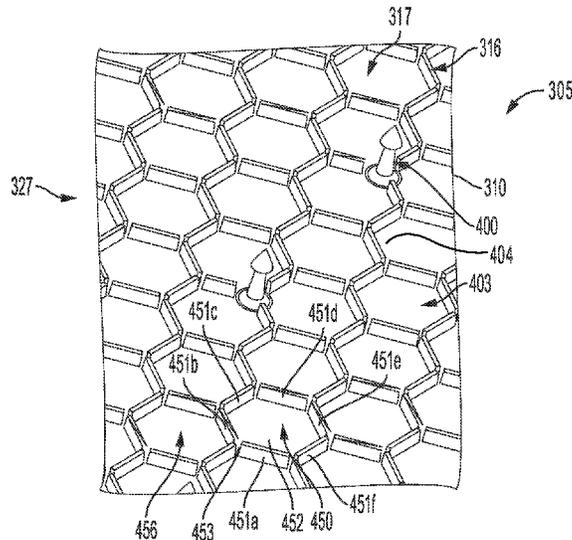
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(57) **ABSTRACT**

In one example of the present disclosure, a radome assembly for use with an antenna assembly is described. The radome assembly may comprise a radome body portion having a first surface and a second surface, wherein the second surface is opposite the first surface, and wherein the radome body portion defines a portion of a housing for an antenna assembly. The radome assembly may further comprise a radome spacer portion extending from the second surface of the radome body portion, the radome spacer portion defining a plurality of cells that are formed from a plurality of cell walls, wherein at least two cell walls of the plurality of cell walls defining each cell of the plurality of cells are spaced apart from each other.

17 Claims, 16 Drawing Sheets



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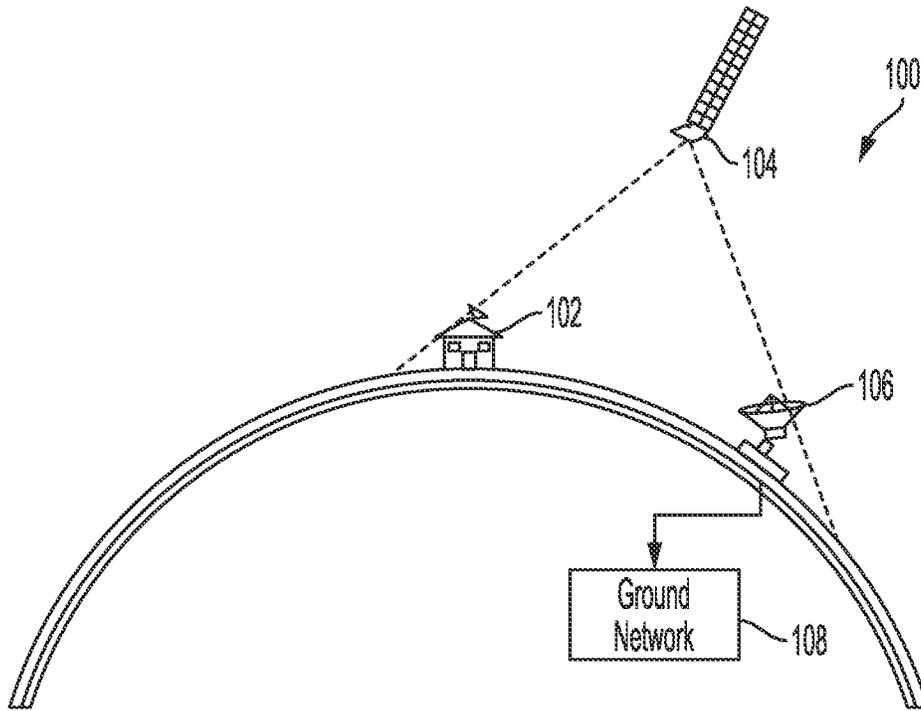


FIG. 1

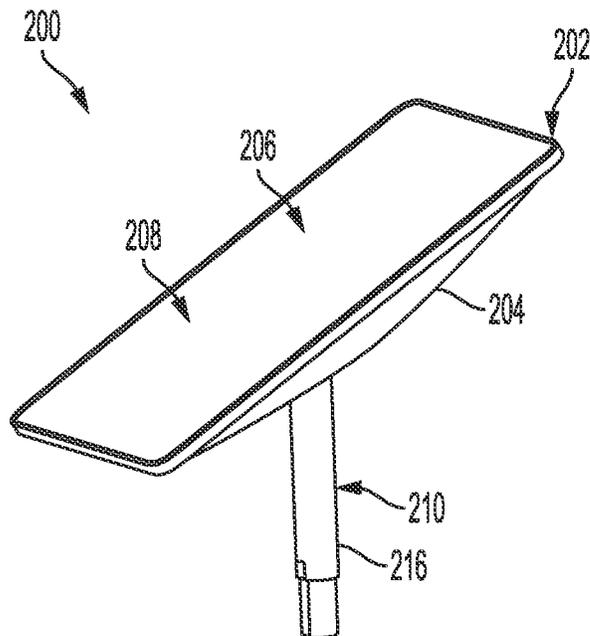


FIG. 2A

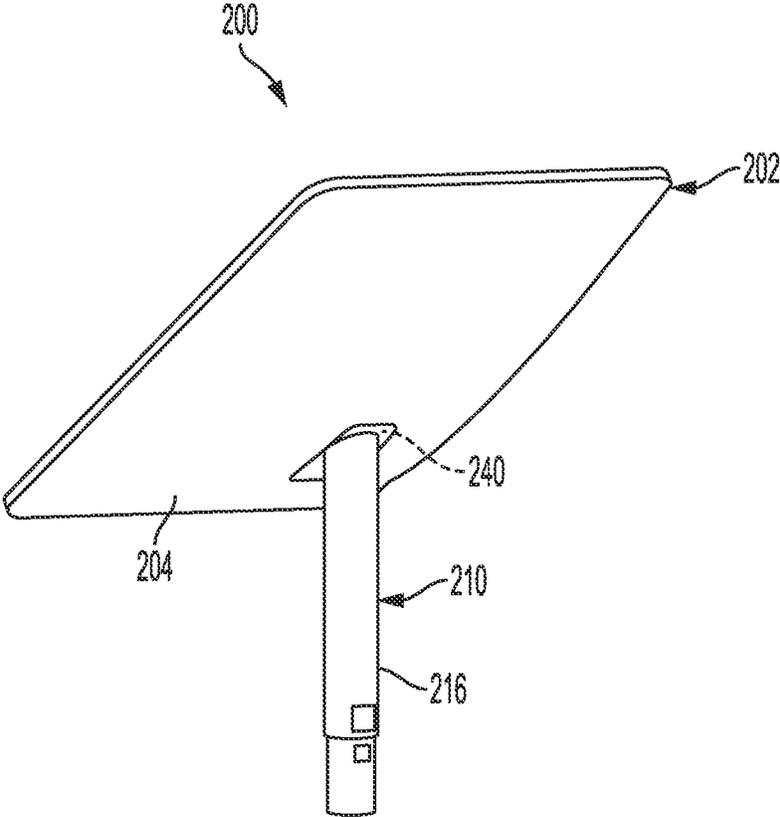


FIG. 2B

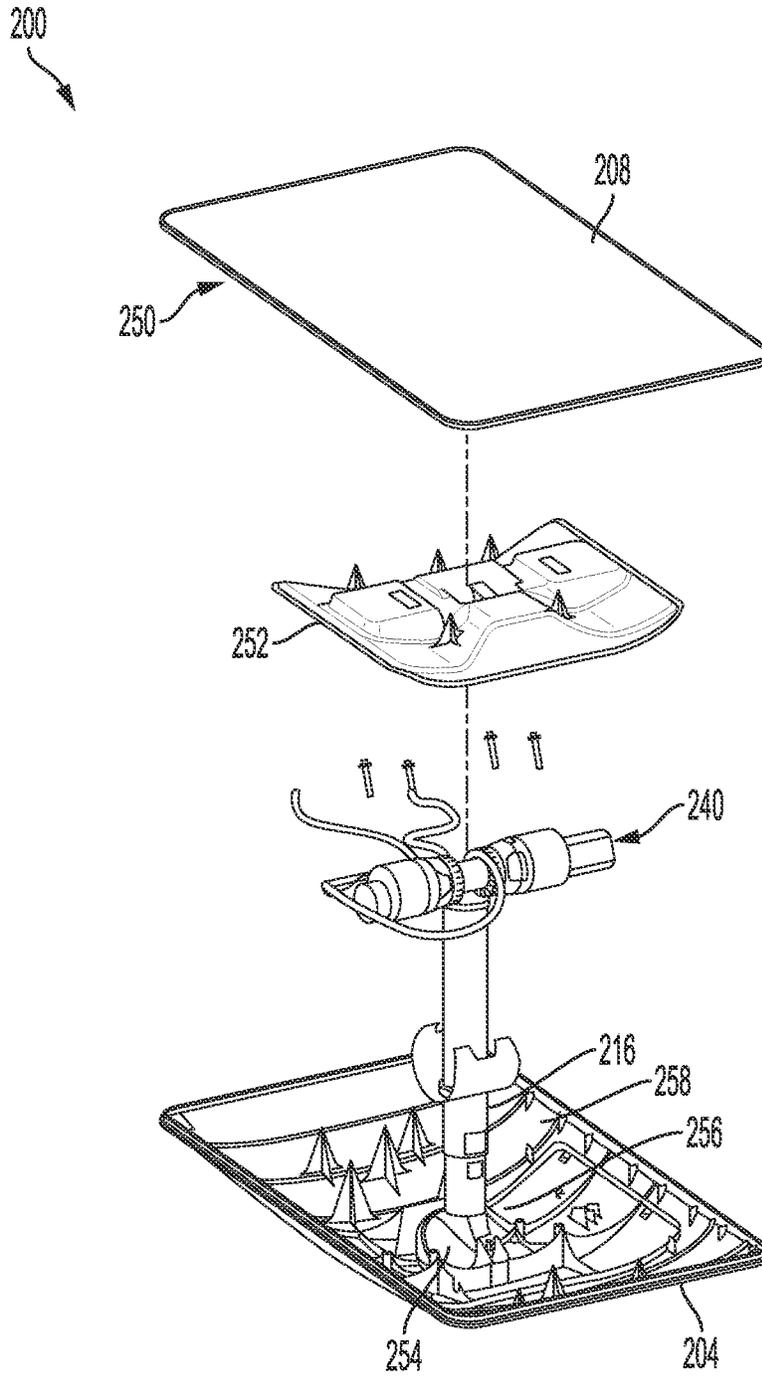


FIG. 3A

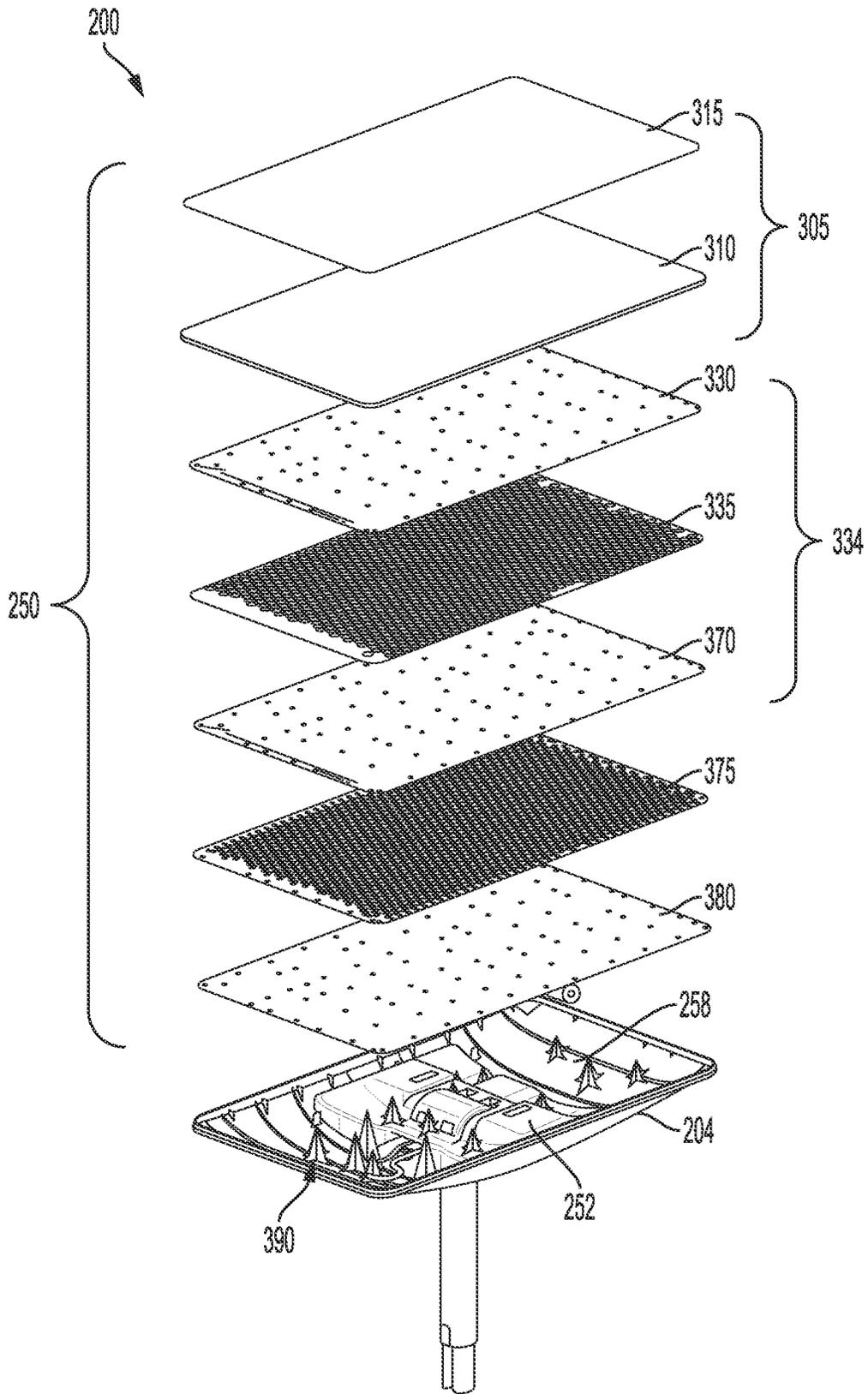
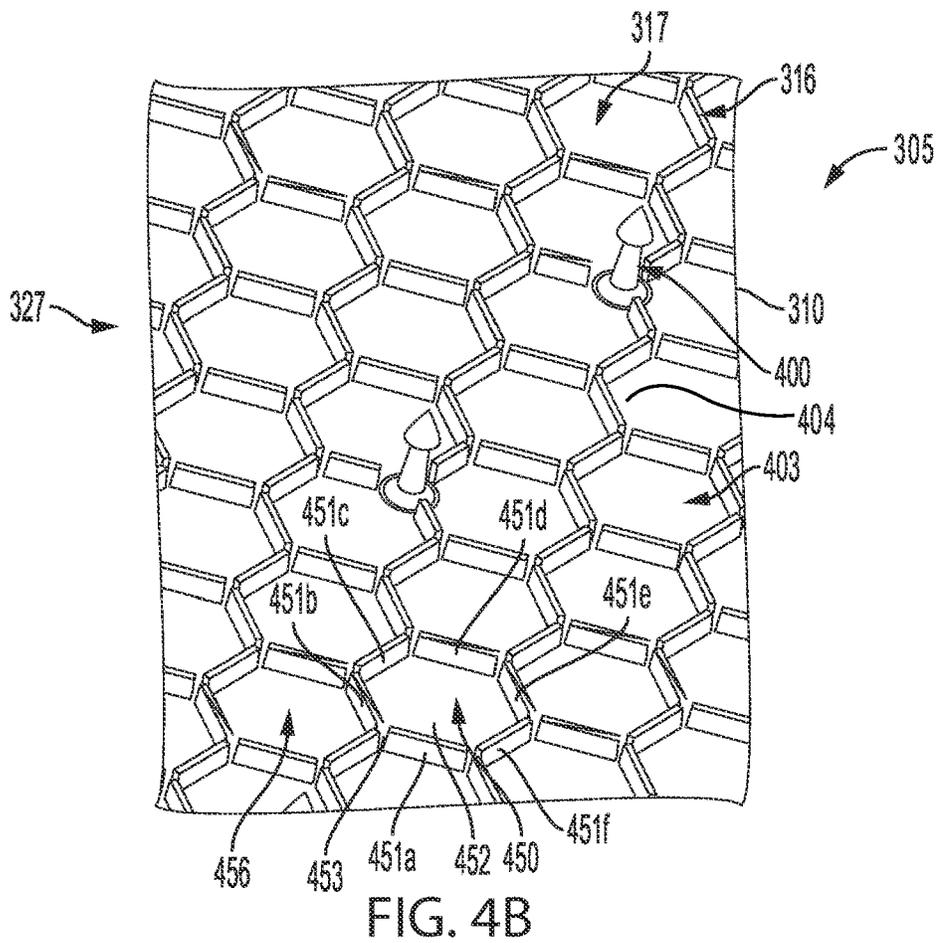
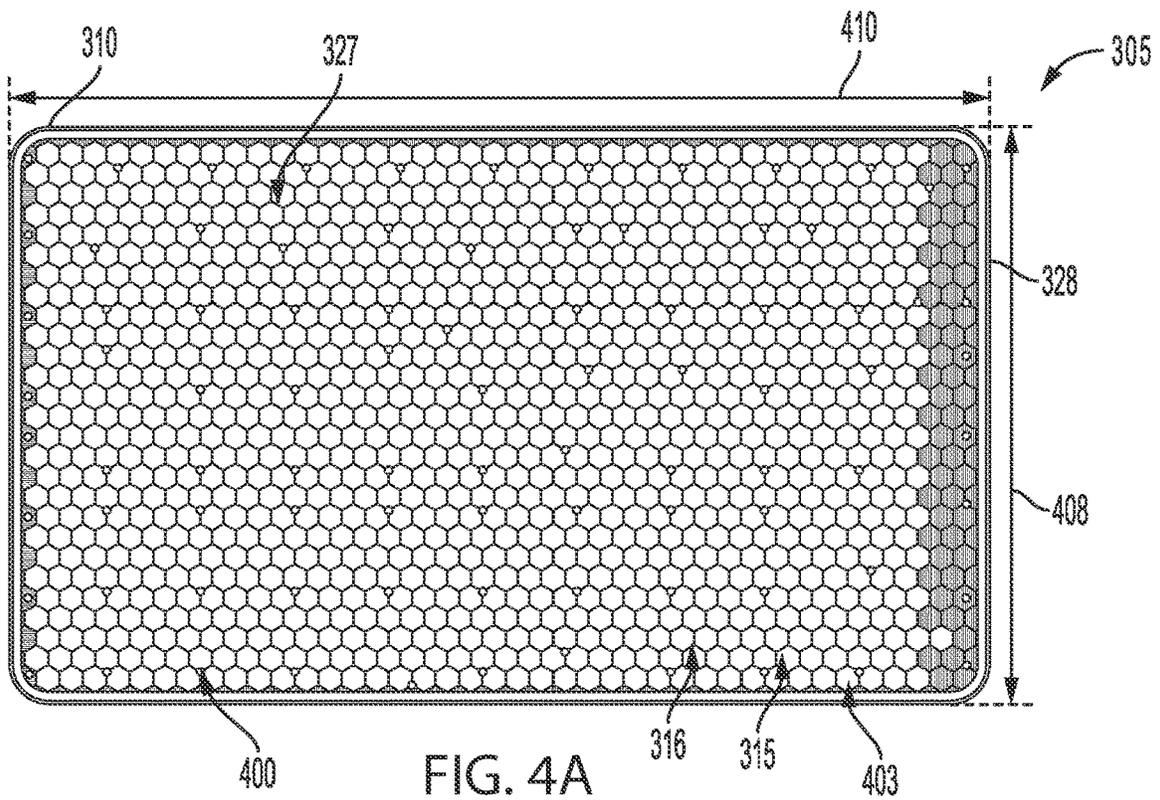


FIG. 3B



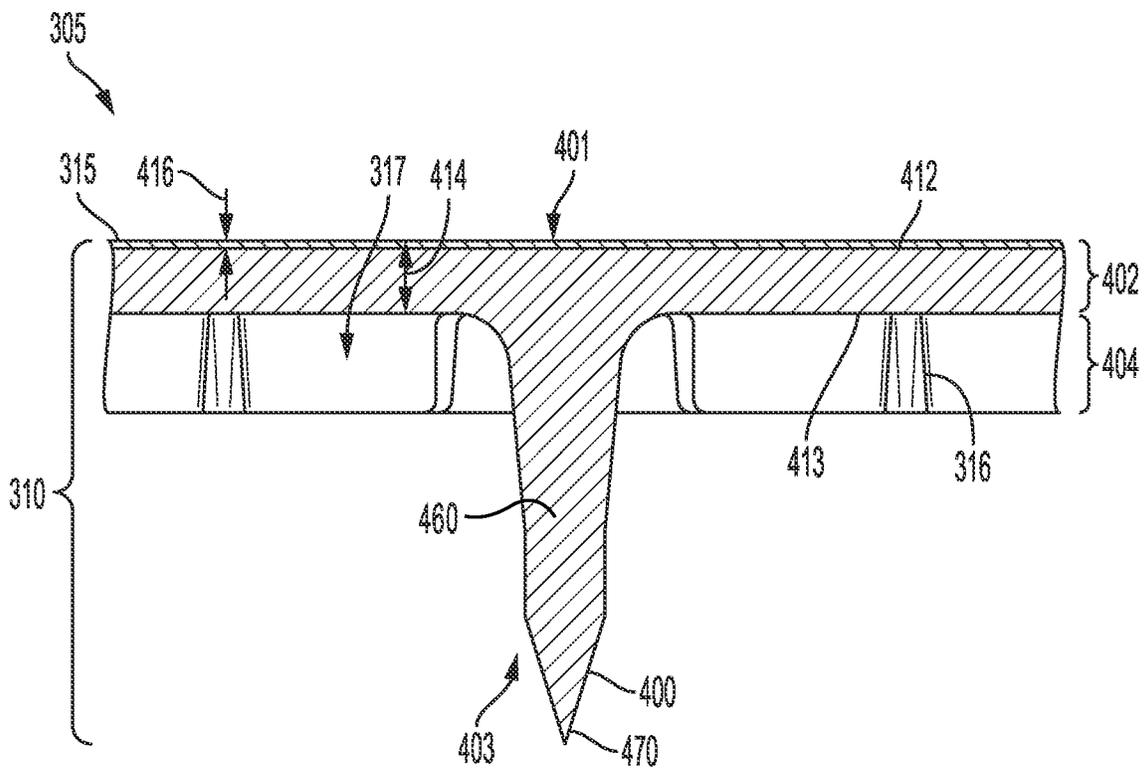


FIG. 5

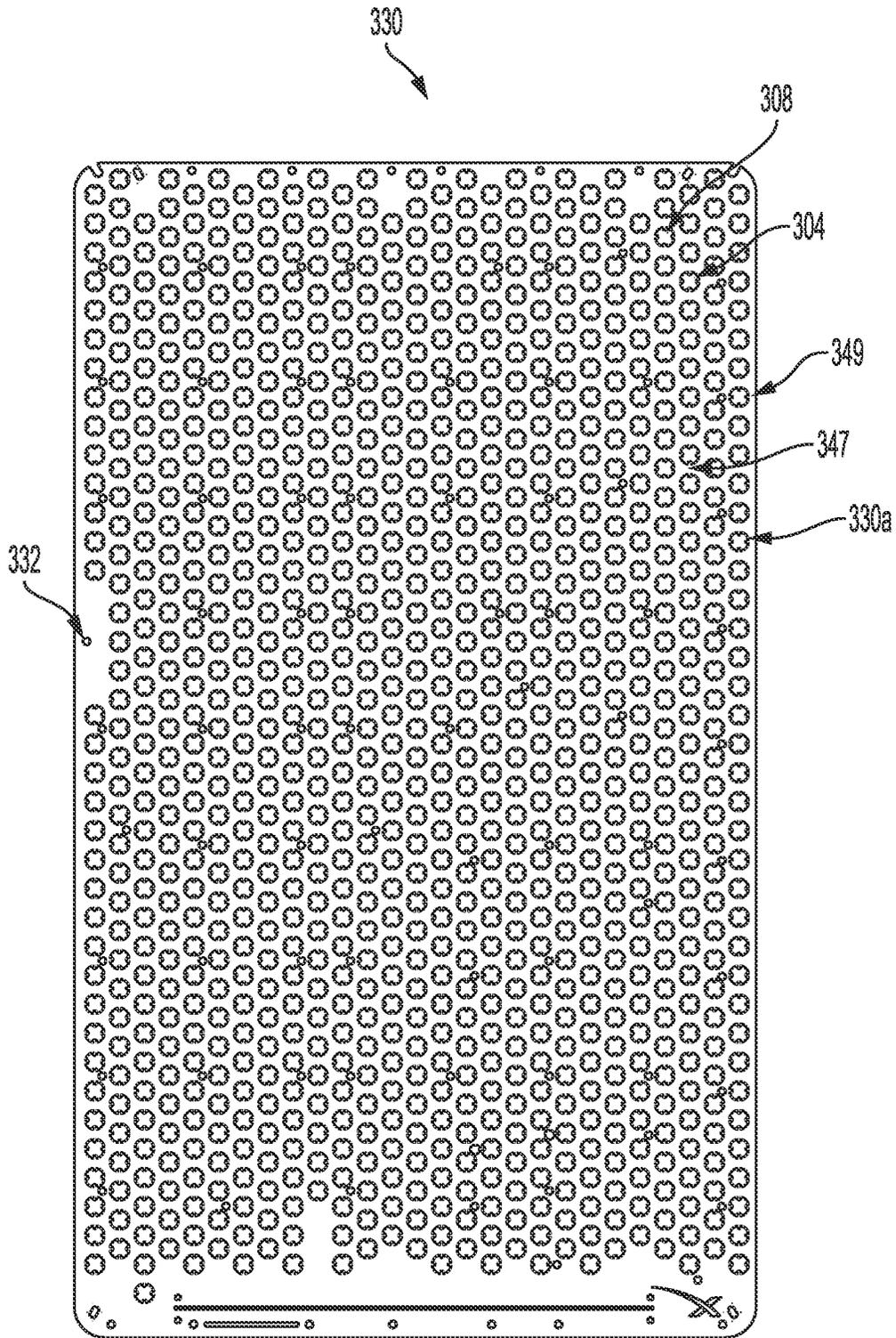


FIG. 6A

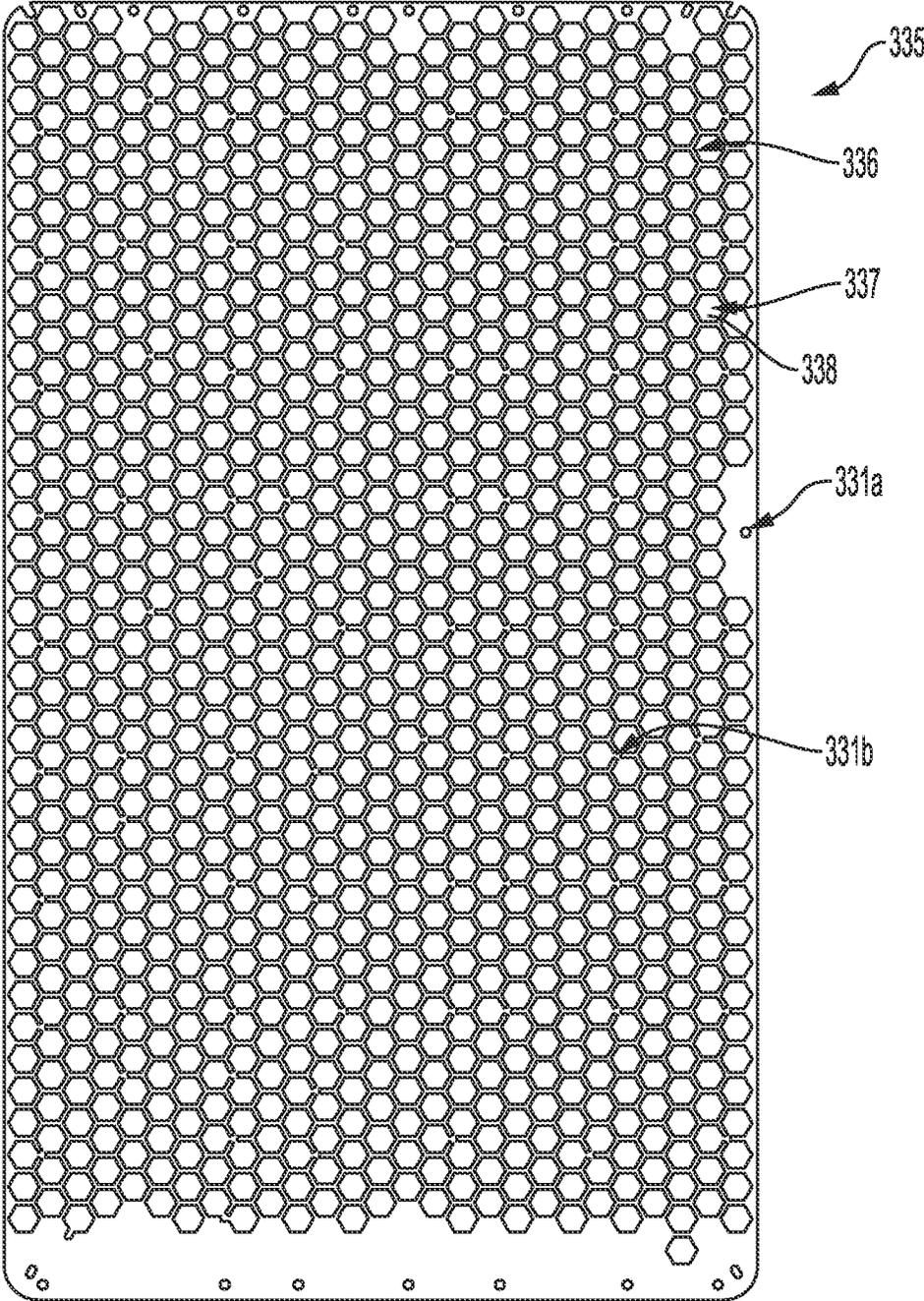


FIG. 6B

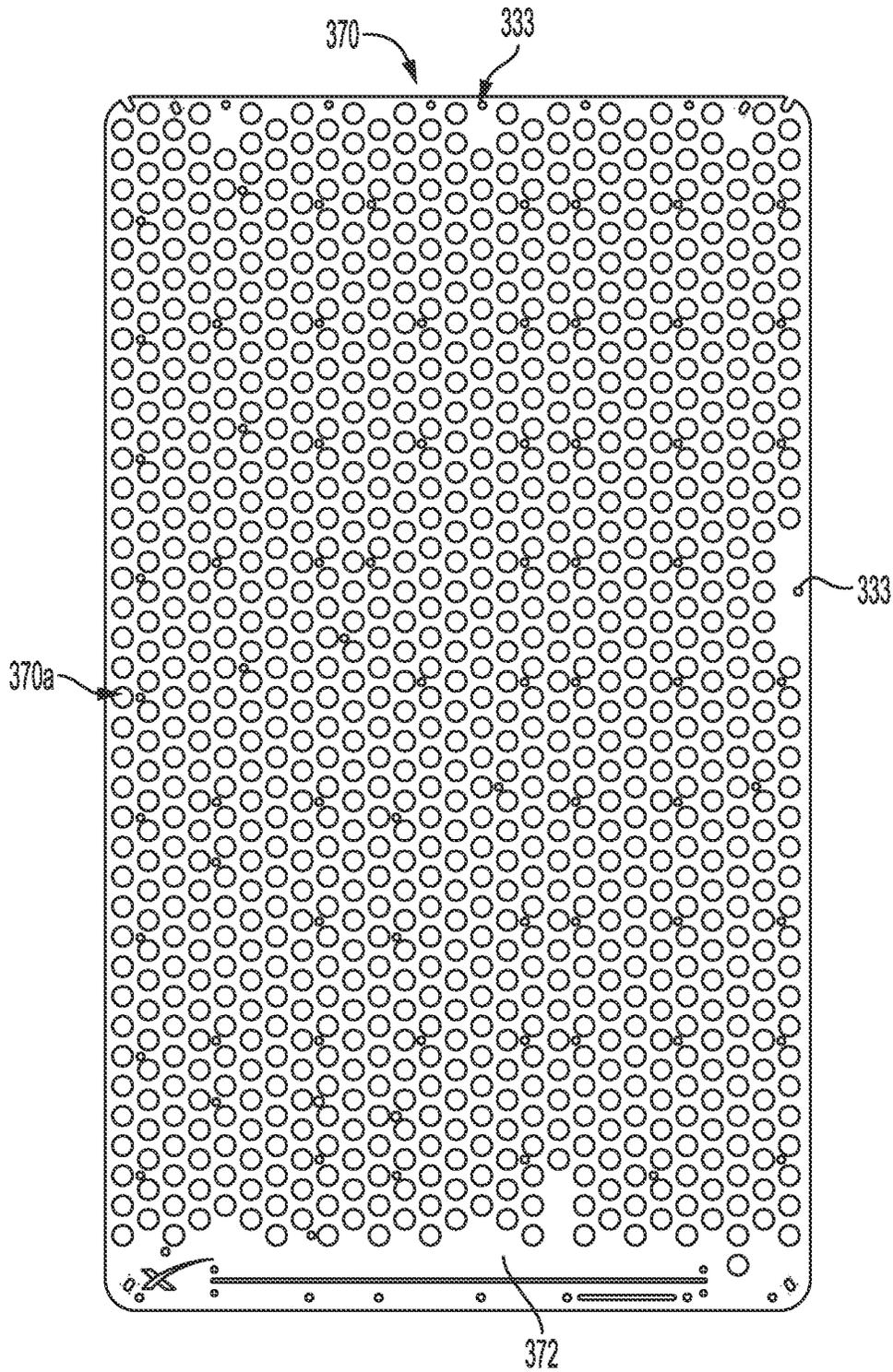


FIG. 6C

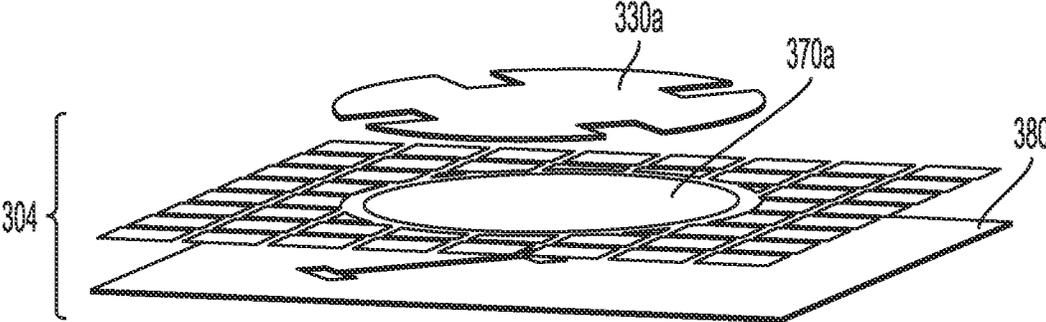


FIG. 7A

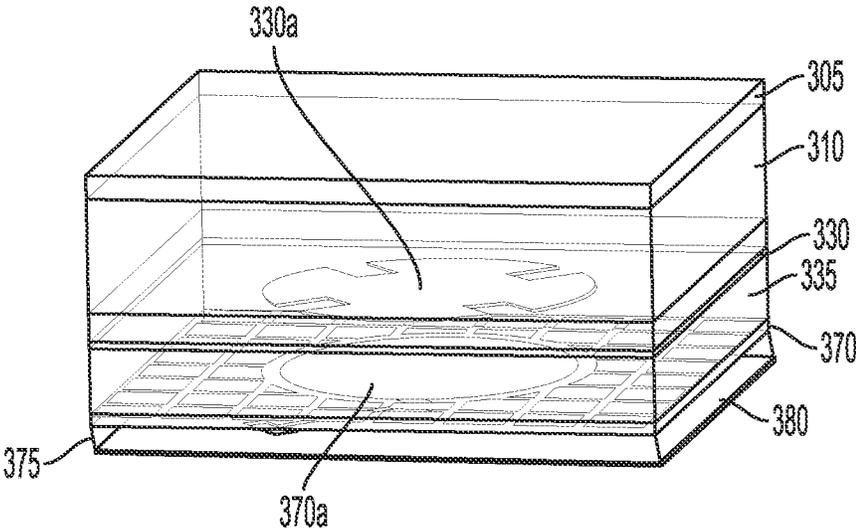


FIG. 7B

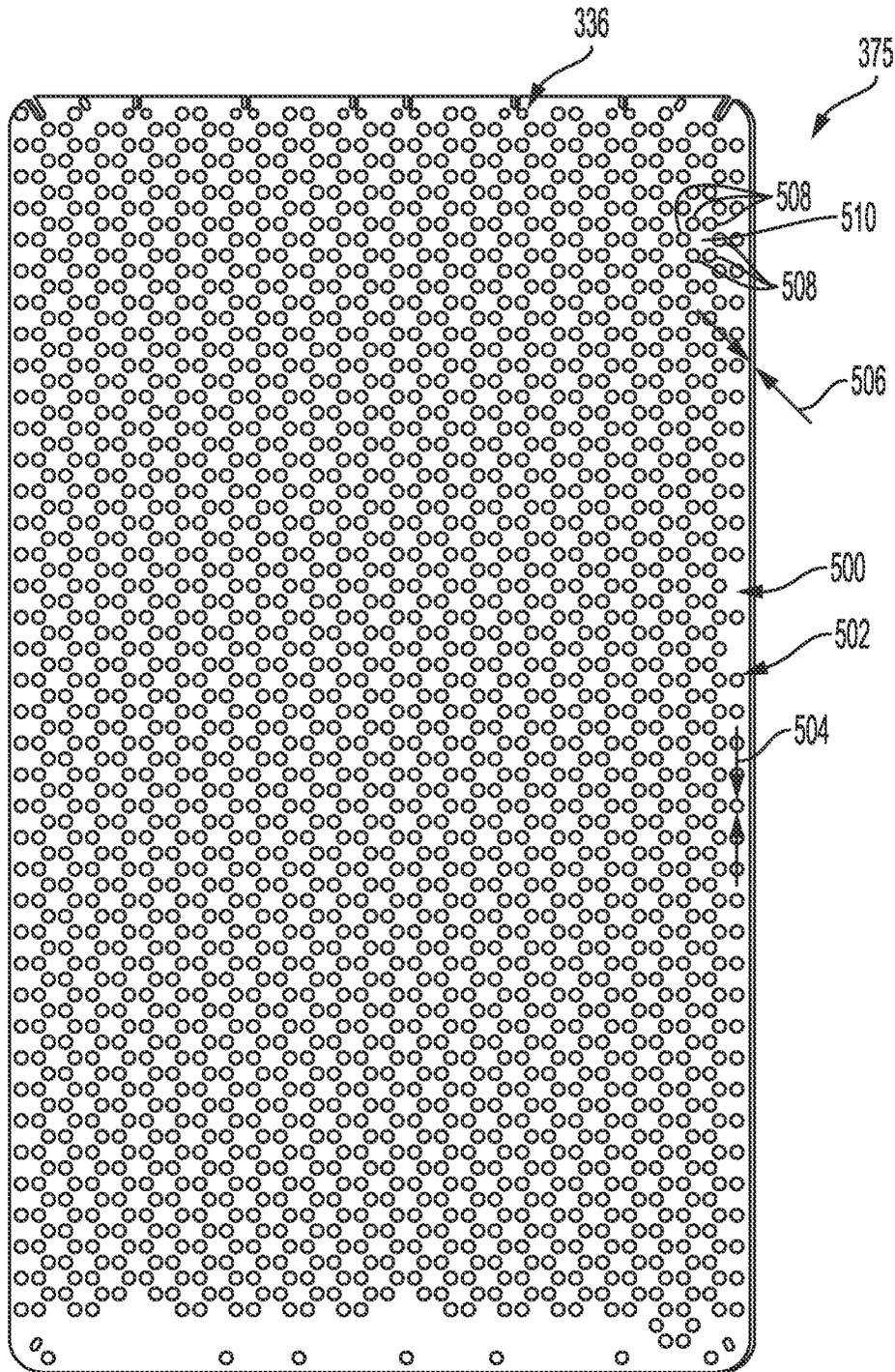


FIG. 8A

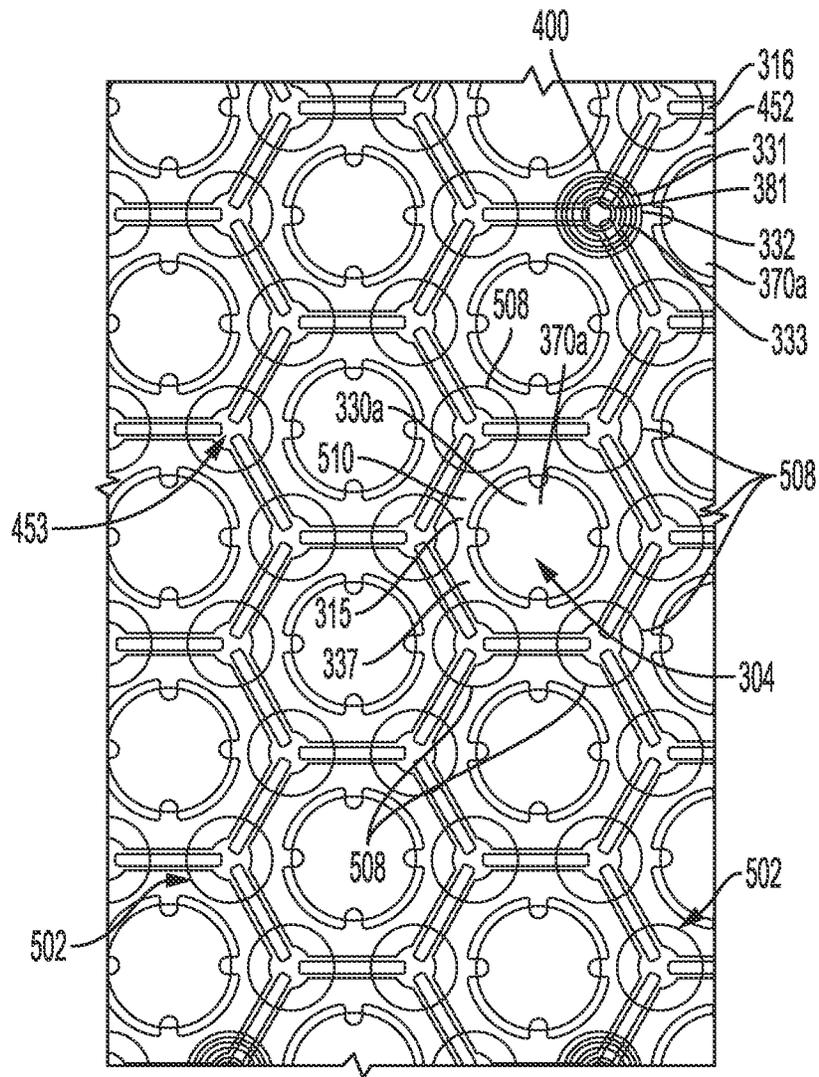


FIG. 8B

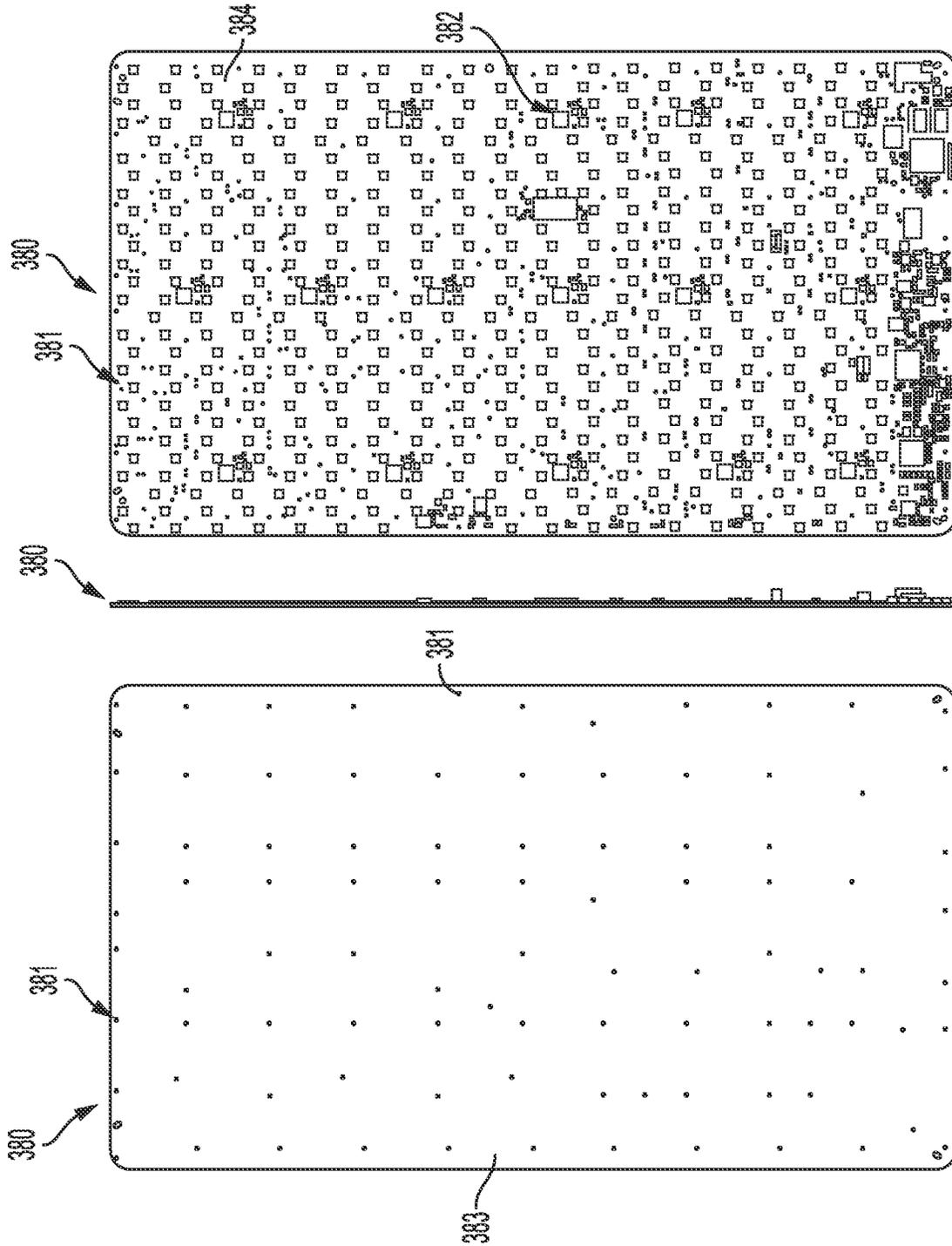


FIG. 9C

FIG. 9B

FIG. 9A

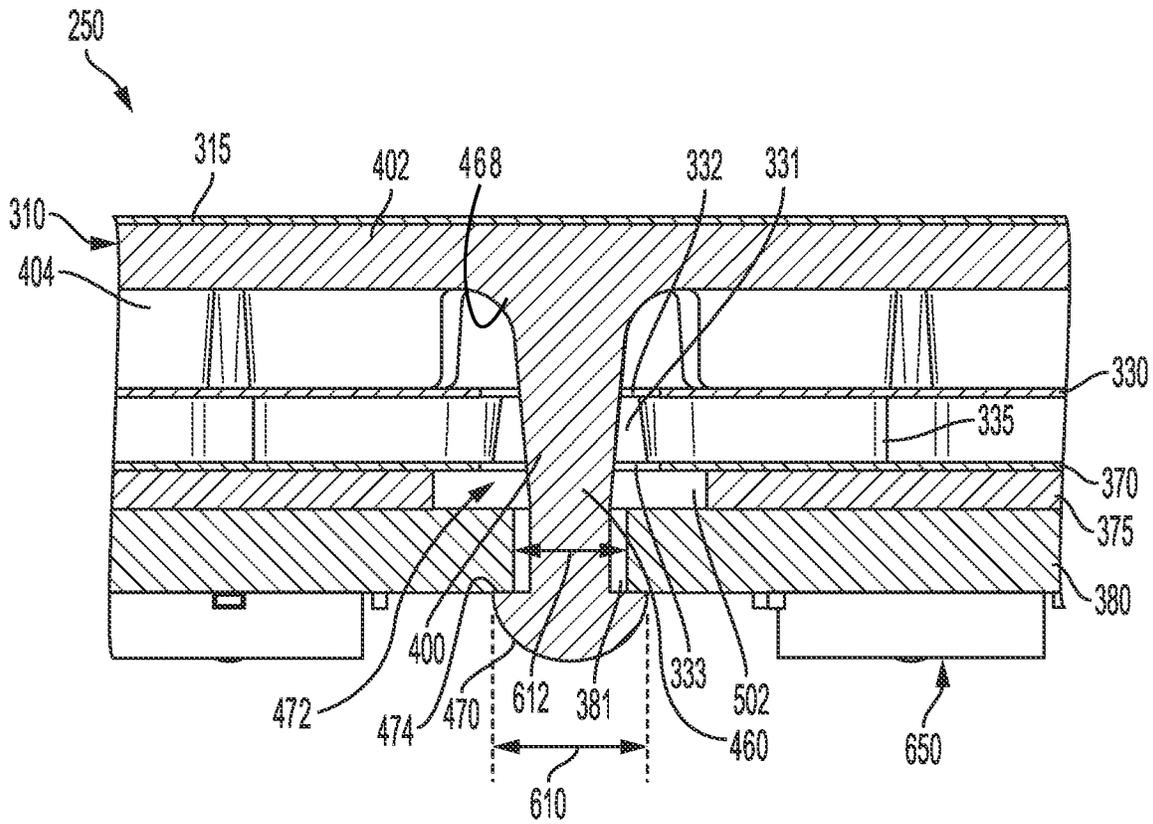


FIG. 10

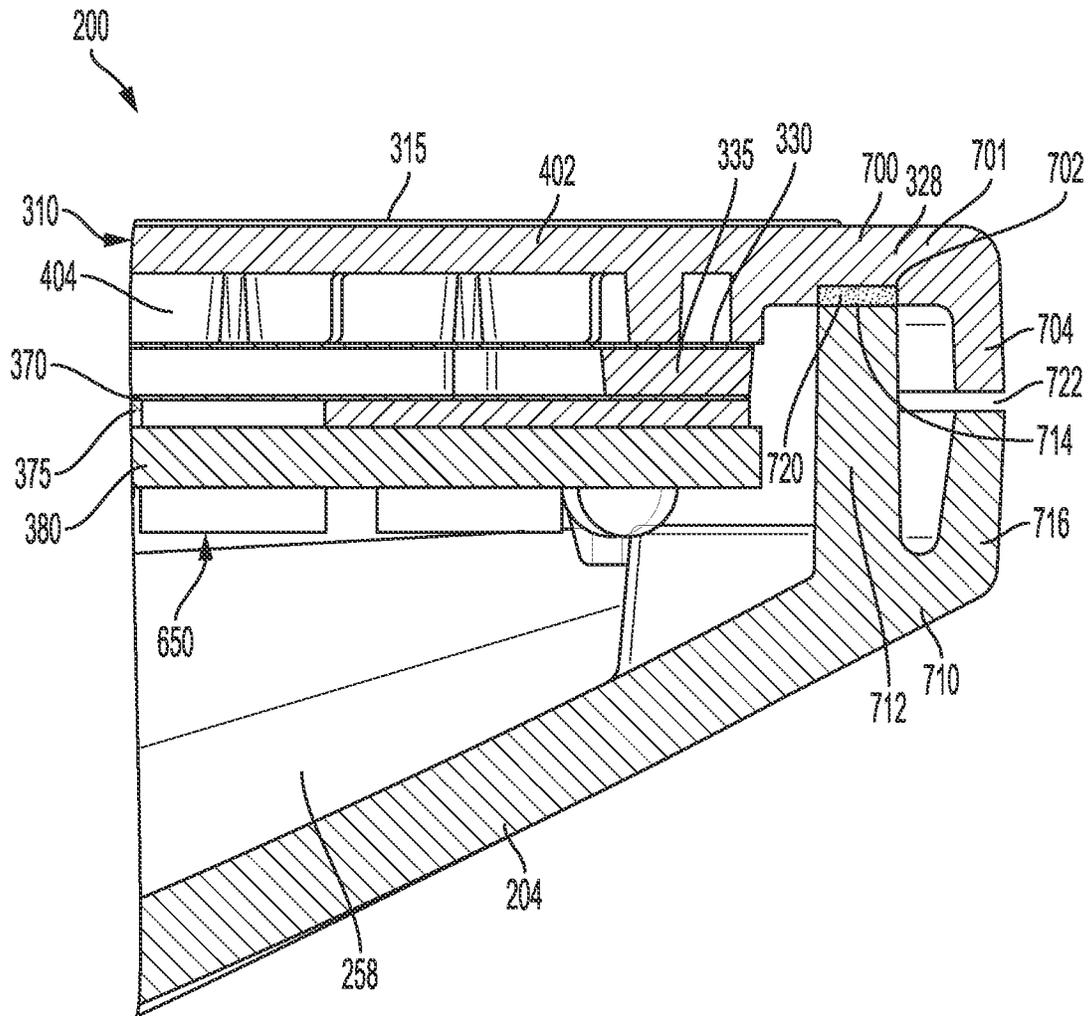


FIG. 11

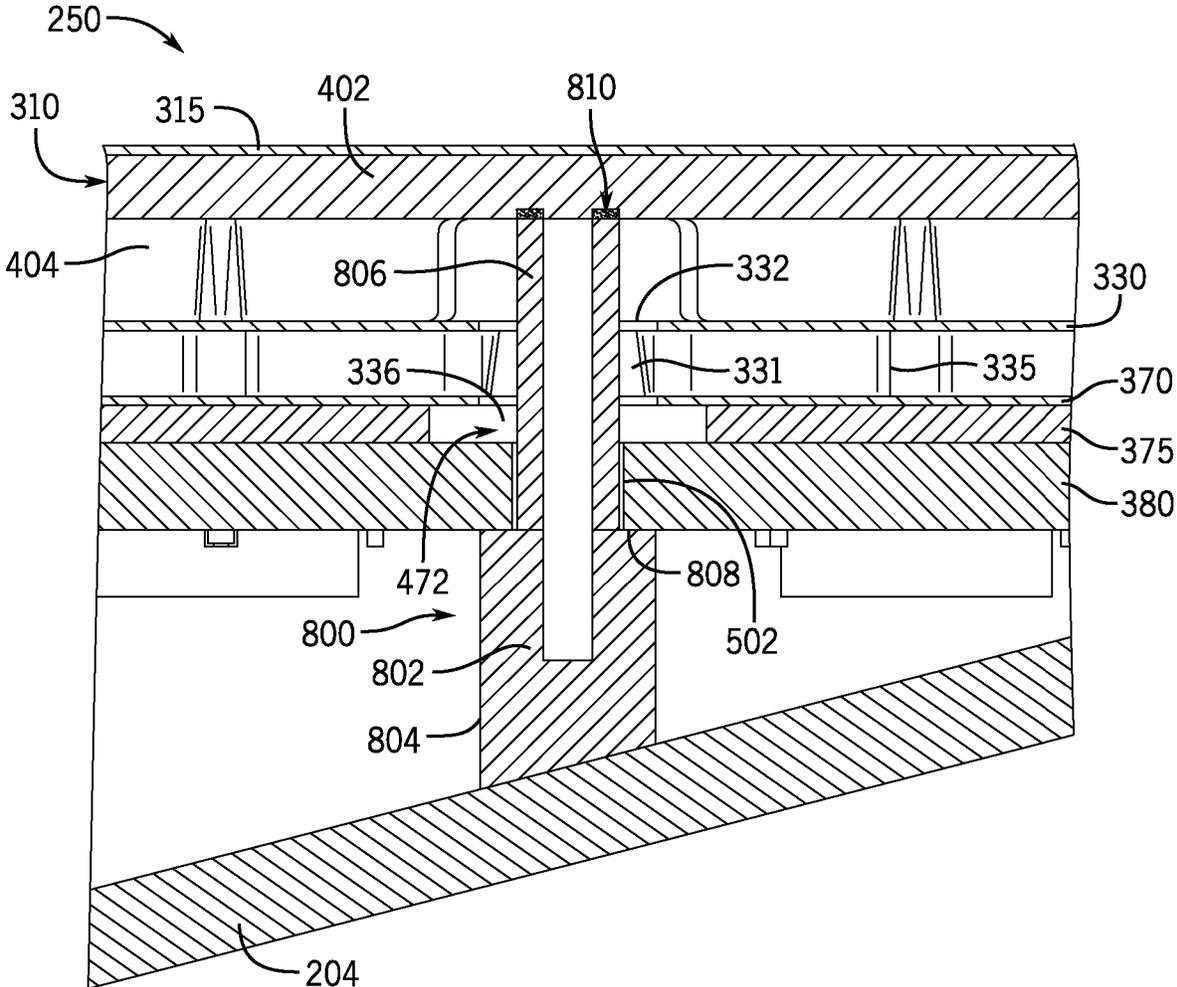


FIG. 12

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RADOME ASSEMBLY HAVING NODELESS CELLS**CROSS-REFERENCE TO RELATED APPLICATION**

This application claims the benefit of U.S. Provisional Application No. 63/277,467, filed Nov. 9, 2021, the disclosure of which is hereby expressly incorporated by reference herein in its entirety.

FIELD

The present disclosure pertains to antenna apparatuses for satellite communication systems.

BACKGROUND

Satellite communication systems generally involve Earth-based antennas in communication with a constellation of satellites in orbit. Earth-based antennas are, of consequence, exposed to weather and other environmental conditions. Therefore, described herein are antenna apparatuses and their housing assemblies designed to be both functional and durable to protect internal antenna elements from environmental conditions while enabling radio frequency communications with a satellite communication system, such as a constellation of satellites.

SUMMARY

This summary is provided to introduce a selection of concepts in a simplified form that are further described below in the detailed description. This summary is not intended to identify key features of the claimed subject matter, nor is it intended to be used as an aid in determining the scope of the claimed subject matter.

In accordance with one embodiment of the present disclosure, a radome assembly for use with an antenna assembly is described. The radome assembly may comprise a radome body portion having a first side and a second side, wherein the radome body portion defines a portion of a housing for an antenna assembly. The radome assembly may further comprise an outer layer coupled to the first side of the radome body portion, wherein the outer layer is made from a different material than the radome body portion, and wherein at least a portion of the outer layer is exposed to an outdoor environment and has hydrophobic properties.

In accordance with one embodiment of the present disclosure, a radome assembly for use with an antenna assembly is described. The radome assembly may comprise a radome body portion having a first side and a second side. The radome assembly may further comprise an outer layer coupled to the first side of the radome body portion, wherein the outer layer is made from a different material than the radome body portion, and wherein at least a portion of the outer layer has hydrophobic properties. The radome assembly may further comprise a radome spacer portion extending from the second side of the radome body portion and configured to space the radome body portion and the outer layer from antenna elements of the antenna assembly.

In accordance with one embodiment of the present disclosure, a method of assembling a radome assembly is described. The method may comprise obtaining a radome body portion having a first side and a second side. The method may further comprise coupling an outer layer to the radome body portion by positioning a surface of the outer

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layer having a pressure sensitive adhesive (PSA) adjacent to the first side of the radome body portion and applying pressure to the outer layer.

In accordance with one embodiment of the present disclosure, a radome assembly for use with an antenna assembly is described. The radome assembly may comprise a radome body portion having a first surface and a second surface, wherein the second surface is opposite the first surface, and wherein the radome body portion defines a portion of a housing for an antenna assembly. The radome assembly may further comprise a radome spacer portion extending from the second surface of the radome body portion, the radome spacer portion defining a plurality of cells that are formed from a plurality of cell walls, wherein at least two cell walls of the plurality of cell walls defining each cell of the plurality of cells are spaced apart from each other.

In accordance with one embodiment of the present disclosure, a radome assembly for use with an antenna assembly is described. The radome assembly may comprise a radome body portion having a first surface and a second surface, wherein the second surface is opposite the first surface. The radome assembly may further comprise a radome spacer portion extending from the second surface of the radome body portion, the radome spacer portion defining a plurality of cells that are formed from a plurality of cell walls, wherein the plurality of cells are nodeless cells.

In accordance with one embodiment of the present disclosure, a radome spacer portion for spacing a radome body portion from antenna elements of an antenna assembly is described. The radome spacer portion may comprise a plurality of cells that are formed from a plurality of cell walls, wherein at least two cell walls of the plurality of cell walls defining each cell of the plurality of cells are spaced apart from each other.

In accordance with one embodiment of the present disclosure, a radome body assembly for use with an antenna assembly is described. The radome body assembly may comprise a radome body portion having a first surface and a second surface, wherein the second surface is opposite the first surface, and wherein the radome body portion defines a portion of a housing for an antenna assembly. The radome body assembly may further comprise a plurality of elongated members each coupled to the second surface of the radome body portion and each having a proximal end at or near the radome body portion and a distal end distal from the radome body portion, wherein the plurality of elongated members is configured to extend through a plurality of corresponding thru-holes defined in the antenna assembly.

In accordance with one embodiment of the present disclosure, a method of assembling an antenna apparatus having an antenna assembly is described. The method may comprise obtaining a radome assembly including at least a radome body portion and a plurality of elongated members, each of the plurality of elongated members having a proximal end at or near the radome body portion and a distal end distal from the radome body portion. The method may further comprise extending each of the plurality of elongated members through a respective thru-hole of a plurality of thru-holes defined in the antenna assembly. The method may further comprise supporting the antenna assembly on respective shoulders defined on at least some of the plurality of elongated members.

In accordance with one embodiment of the present disclosure, a housing for an antenna assembly is described. The housing may comprise a radome body assembly and a lower enclosure that is coupled to the radome body assembly using

welding such that a volume is defined between the radome body assembly and the lower enclosure.

In accordance with one embodiment of the present disclosure, a method of assembling an antenna assembly is described. The method may comprise obtaining a radome body assembly, a lower enclosure, and at least one antenna layer. The method may further comprise positioning the at least one antenna layer in a volume defined between the top portion and the lower enclosure. The method may further comprise coupling, using vibration welding, the top portion to the lower enclosure to enclose the at least one antenna layer within the volume.

In accordance with one embodiment of the present disclosure, a dielectric layer for use in an antenna assembly is described. The dielectric layer may comprise a planar body formed using a dielectric material. The dielectric layer may further comprise a plurality of openings defined in the planar body and surrounding a plurality of portions of the dielectric material, each of the plurality of portions of the dielectric material being configured to be aligned with an antenna element of a plurality of antenna elements of the antenna assembly.

In accordance with one embodiment of the present disclosure, an antenna assembly is described. The antenna assembly may comprise a printed circuit board (PCB) assembly. The antenna assembly may further comprise at least one antenna layer at least partially forming a plurality of antenna elements. The antenna assembly may further comprise a dielectric layer located between the PCB assembly and the at least one antenna layer and having a dielectric constant of between 2.5 and 3.5 and a coefficient of thermal expansion (CTE) of between 15 parts per million per degree Celsius (ppm/° C.) and 25 ppm/° C.

In accordance with one embodiment of the present disclosure, a method of assembling an antenna assembly is described. The method may comprise obtaining at least one antenna layer at least partially forming a plurality of antenna elements. The method may further comprise obtaining a printed circuit board (PCB) assembly. The method may further comprise obtaining a dielectric layer having a planar body formed using a dielectric material, and a plurality of openings defined by the planar body and surrounding a plurality of portions of the dielectric material. The method may further comprise stacking the dielectric layer between the at least one antenna layer and the PCB assembly such that each of the plurality of portions of the dielectric material is aligned with an antenna element of the plurality of antenna elements.

In any of the embodiments described herein, the outer layer may have a thickness that is less than or equal to 60 thousandths of an inch.

In any of the embodiments described herein, the radome assembly may have a thickness of greater than 3 mm.

In any of the embodiments described herein, the outer layer may be coupled to the first surface of the radome body portion using an adhesive.

In any of the embodiments described herein, the adhesive may be a pressure sensitive adhesive (PSA).

In any of the embodiments described herein, the outer layer may include an ultraviolet (UV) light blocking additive.

In any of the embodiments described herein, the ultraviolet (UV) light blocking additive may be titanium dioxide (TiO₂).

In any of the embodiments described herein, at least a portion of the outer layer may have superhydrophobic properties.

In any of the embodiments described herein, the outer layer may have superhydrophobic properties.

In any of the embodiments described herein, the radome body portion and the radome spacer portion may be integrally formed.

In any of the embodiments described herein, the radome body portion and the radome spacer portion may be formed from a different material than the outer layer.

In any of the embodiments described herein, the radome assembly may further comprise a plurality of elongated members each coupled to the second side of the radome body portion and each having a proximal end at or near the radome body portion and a distal end extending away from the radome body portion, wherein the distal end of each of the plurality of elongated members may be configured to extend through an opening defined in the antenna assembly.

In any of the embodiments described herein, at least one elongated member of the plurality of elongated members may be configured to interface with the antenna assembly to resist separation of the radome body portion from the antenna assembly.

In any of the embodiments described herein, the plurality of elongated members may be further configured to port thermal energy from the antenna assembly to the radome body portion.

In any of the embodiments described herein, the radome body portion and the radome spacer portion may be formed using a first material.

In any of the embodiments described herein, the radome body portion and the radome spacer portion may be formed using the same material.

In any of the embodiments described herein, the first material may include a polymer.

In any of the embodiments described herein, the polymer may include at least one of polypropylene (PP), polycarbonates, polybutylene terephthalate (PBT), polyphenylene ether (PPE), poly(p-phenylene oxide) (PPO), polystyrene (PS), polyethylene terephthalate (PET), polyvinyl chloride (PVC), and liquid crystal polymer (LCP).

In any of the embodiments described herein, each of the cell walls that define a first cell may also function as a cell wall of at least another cell of the plurality of cells.

In any of the embodiments described herein, each of the plurality of cells may be defined by 6 cell walls.

In any of the embodiments described herein, a vertical pathway of each of the plurality of cells may be configured to be aligned with a respective antenna element of the antenna assembly.

In any of the embodiments described herein, the first surface may be a planar surface.

In any of the embodiments described herein, the plurality of cells may be nodeless cells.

In any of the embodiments described herein, the radome assembly may have a thickness of greater than or equal to 3 mm.

In any of the embodiments described herein, the radome assembly may further comprise a hydrophobic outer layer coupled to the first surface of the radome body portion.

In any of the embodiments described herein, the radome body portion and the radome spacer portion may be formed from a first material and the hydrophobic outer layer may be formed by a second material.

In any of the embodiments described herein, at least one elongated member of the plurality of elongated members may be configured to interface with the antenna assembly to resist separation of the radome body portion from the antenna assembly.

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In any of the embodiments described herein, at least one elongated member of the plurality of elongated members may include a shoulder.

In any of the embodiments described herein, the antenna assembly may include a plurality of layers each having a plurality of ports.

In any of the embodiments described herein, the plurality of ports of each of the plurality of layers may align to define a plurality of thru-holes in the antenna assembly.

In any of the embodiments described herein, the plurality of elongated members may further be configured to conduct thermal energy from the antenna assembly to the radome body portion.

In any of the embodiments described herein, the antenna assembly may include one or more components configured to generate thermal energy and/or configured to couple to electronic components configured to generate thermal energy, such that the plurality of elongated members conduct the thermal energy generated from the antenna assembly to the radome body portion.

In any of the embodiments described herein, the radome body portion and the plurality of elongated members may be integrally formed or separately formed.

In any of the embodiments described herein, the distal ends of the plurality of elongated members may be coupled to the antenna assembly.

In any of the embodiments described herein, the distal ends of the plurality of elongated members may be each deformable, such that deformation of the distal end while the at least one elongated member is extended through a corresponding thru-hole of the antenna assembly defines a shoulder that resists separation of the radome body portion from the second element of the antenna assembly.

In any of the embodiments described herein, the respective distal ends of the plurality of elongated members may be coupled to a lower enclosure, wherein the lower enclosure may define a portion of the housing for the antenna assembly.

In any of the embodiments described herein, the radome body assembly may further comprise a radome spacer portion extending from the second surface of the radome body portion, the radome spacer portion defining a plurality of cells that are formed from a plurality of cell walls.

In any of the embodiments described herein, at least two cell walls of the cell walls defining each cell of the plurality of cells may be spaced apart from each other.

In any of the embodiments described herein, the plurality of elongated members may extend further from the radome body portion than the plurality of cell walls.

In any of the embodiments described herein, the radome spacer portion, the radome body portion, and the plurality of elongated members may be integrally formed.

In any of the embodiments described herein, the plurality of elongated members may be coupled to the radome assembly either before or after extending each of the plurality of elongated members through a respective thru-hole of a plurality of thru-holes defined in the antenna assembly.

In any of the embodiments described herein, the respective shoulders defined on at least some of the plurality of elongated members may be formed by deforming at least some of the distal ends of each of the elongated members.

In any of the embodiments described herein, the welding may be vibration welding or ultrasonic welding.

In any of the embodiments described herein, the radome body assembly may include a bonding surface located at or near a perimeter portion of the radome body assembly.

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In any of the embodiments described herein, the lower enclosure may include a post extending away from a perimeter portion of the lower enclosure and defining a bonding edge configured to be coupled to the bonding surface of the radome body assembly via the welding.

In any of the embodiments described herein, the lower enclosure may further include an enclosure lip located outward relative to the post and extending substantially parallel to the post, and wherein the radome body assembly may further include a radome lip extending away from the bonding surface such that a gap is defined between the enclosure lip and the radome lip when the bonding surface is coupled to the bonding edge.

In any of the embodiments described herein, the bonding surface may extend around the entire perimeter portion of the radome body assembly, and the post and bonding edge defined thereon may extend around the entire perimeter portion of the lower enclosure.

In any of the embodiments described herein, the welding between the bonding surface and the bonding edge may form a hermetic seal between the radome body assembly and the lower enclosure.

In any of the embodiments described herein, the radome body assembly may include a radome body portion and a radome spacer portion coupled to the radome body portion, wherein the bonding surface may be defined by the radome body portion and wherein the radome spacer portion may be configured to be located within the volume when the radome body portion is coupled to the lower enclosure.

In any of the embodiments described herein, the bonding surface may extend substantially parallel to the radome body portion and the post may extend substantially perpendicular to the radome body portion.

In any of the embodiments described herein, the dielectric layer may be configured to be positioned between a printed circuit board (PCB) assembly and at least one antenna layer that at least partially forms the antenna assembly.

In any of the embodiments described herein, each of the plurality of openings may have a circular shape.

In any of the embodiments described herein, the dielectric material may have a dielectric constant of between 2.5 and 3.5.

In any of the embodiments described herein, the dielectric material may have a coefficient of thermal expansion (CTE) of between 15 parts per million per degree Celsius (ppm/^oC.) and 25 ppm/^oC.

In any of the embodiments described herein, the plurality of portions of the dielectric material may be surrounded by 6 openings of the plurality of openings.

In any of the embodiments described herein, the plurality of openings may increase a scan angle of the antenna assembly by at least 1.5 percent.

In any of the embodiments described herein, the dielectric layer may include a planar body; and a plurality of openings defined by the planar body and surrounding a plurality of portions of the dielectric material.

In any of the embodiments described herein, each of the plurality of portions of the dielectric material may be aligned with an antenna element of the plurality of antenna elements.

In any of the embodiments described herein, the plurality of openings may increase a scan angle of the antenna assembly by at least 1.5 percent.

In any of the embodiments described herein, the dielectric material may have flame retardant properties.

In any of the embodiments described herein, the dielectric material may include at least about 5% decabromodiphenyl ethane (DBDPE).

In any of the embodiments described herein, each of the plurality of openings may have a circular shape.

In any of the embodiments described herein, the method may further comprise coupling the at least one antenna layer, the PCB assembly, and the dielectric layer together.

In any of the embodiments described herein, obtaining the dielectric layer may include obtaining the dielectric layer to have a dielectric constant of between 2.5 and 3.5 and a coefficient of thermal expansion (CTE) of between 15 parts per million per degree Celsius (ppm/° C.) and 25 ppm/° C.

DESCRIPTION OF THE DRAWINGS

FIG. 1 is a not-to-scale diagram illustrating a simple example of communication in a satellite communication system in accordance with embodiments of the present disclosure;

FIG. 2A is an isometric top view depicting an exemplary antenna apparatus in accordance with embodiments of the present disclosure;

FIG. 2B is an isometric bottom view depicting exemplary antenna apparatus of FIG. 2A, showing a housing secured to a leg that is designed to be mounted to a surface in accordance with embodiments of the present disclosure;

FIG. 3A is an isometric exploded view depicting a housing assembly of the antenna assembly of FIGS. 2A and 2B in accordance with embodiments of the present disclosure;

FIG. 3B is an isometric exploded view depicting various elements of an antenna stack of the antenna assembly of FIGS. 2A and 2B in accordance with embodiments of the present disclosure;

FIG. 4A is a bottom view of a radome assembly of the antenna assembly of FIGS. 2A and 2B in accordance with embodiments of the present disclosure;

FIG. 4B is an enlarged isometric view of a portion of the bottom of the radome assembly of the antenna assembly of FIGS. 2A and 2B in accordance with embodiments of the present disclosure;

FIG. 5 is a cross-sectional view of a portion of the radome assembly of the antenna assembly of FIGS. 2A and 2B including an outer layer as well as a radome body assembly having a radome body portion, a radome spacer portion, and an elongated member in accordance with embodiments of the present disclosure;

FIG. 6A is a top view of an upper patch antenna layer of the antenna assembly of FIGS. 2A and 2B showing an array of upper patch antenna elements in accordance with embodiments of the present disclosure;

FIG. 6B is a top view illustrating an antenna spacer of the antenna assembly of FIGS. 2A and 2B in accordance with embodiments of the present disclosure;

FIG. 6C is a top view of a lower patch antenna layer of the antenna assembly of FIGS. 2A and 2B showing an array of lower patch antenna elements in accordance with embodiments of the present disclosure;

FIGS. 7A and 7B are isometric views of a single antenna element in an antenna element array of the antenna assembly of FIGS. 2A and 2B in accordance with embodiments of the present disclosure;

FIG. 8A is a top view of a dielectric spacer layer of the antenna assembly of FIGS. 2A and 2B illustrating exemplary locations and sizes of openings formed through the dielectric spacer layer in accordance with embodiments of the present disclosure;

FIG. 8B is an enlarged top view of various elements of the antenna stack of the antenna assembly of FIGS. 2A and 2B illustrating relative locations of cell walls of a radome spacer

portion, openings of a dielectric spacer layer, ports through which elongated members of a radome body assembly extend, and patch antenna elements in accordance with embodiments of the present disclosure;

FIG. 9A is a top view of a printed circuit board (PCB) assembly of the antenna assembly of FIGS. 2A and 2B in accordance with embodiments of the present disclosure;

FIG. 9B is a cross-sectional view of a portion of the PCB assembly of FIG. 9A in accordance with embodiments of the present disclosure;

FIG. 9C is a bottom view of the PCB assembly of FIG. 9A illustrating electronic components of the PCB assembly in accordance with embodiments of the present disclosure;

FIG. 10 is an enlarged cross-sectional view of a center portion of an antenna stack of the antenna assembly of FIGS. 2A and 2B illustrating use of elongated members of a radome body assembly to couple elements of the antenna stack together in accordance with embodiments of the present disclosure;

FIG. 11 is an enlarged cross-sectional view of an edge of the antenna assembly of FIGS. 2A and 2B illustrating the antenna assembly in an assembled state in accordance with embodiments of the present disclosure; and

FIG. 12 is an enlarged cross-sectional view of a center portion of an antenna stack of the antenna assembly of FIGS. 2A and 2B illustrating use of an elongated member to couple elements of the antenna stack together in accordance with embodiments of the present disclosure.

DETAILED DESCRIPTION

Various embodiments of the disclosure are discussed in detail below. While the concepts of the present disclosure are susceptible to various modifications and alternative forms, specific embodiments thereof have been shown by way of example in the drawings and will be described herein in detail. It should be understood, however, that there is no intent to limit the concepts of the present disclosure to the particular forms disclosed, but on the contrary, the intention is to cover all modifications, equivalents, and alternatives consistent with the present disclosure and the appended claims.

In the drawings, some structural or method features may be shown in specific arrangements and/or orderings. However, it should be appreciated that such specific arrangements and/or orderings may not be required. Rather, in some embodiments, such features may be arranged in a different manner and/or order than shown in the illustrative figures. Additionally, the inclusion of a structural or method feature in a particular figure is not meant to imply that such feature is required in all embodiments and, in some embodiments, it may not be included or may be combined with other features.

References in the specification to “one embodiment,” “an embodiment,” “an illustrative embodiment,” etc., indicate that the embodiment described may include a particular feature, structure, or characteristic, but every embodiment may or may not necessarily include that particular feature, structure, or characteristic. Moreover, such phrases are not necessarily referring to the same embodiment. Further, when a particular feature, structure, or characteristic is described in connection with an embodiment, it is submitted that it is within the knowledge of one skilled in the art to affect such feature, structure, or characteristic in connection with other embodiments whether or not explicitly described. Language such as “top,” “bottom,” “upper,” “lower,” “vertical,” “horizontal,” “lateral,” in the present disclosure is meant to

provide orientation for the reader with reference to the drawings and is not intended to be the required orientation of the components or to impart orientation limitations into the claims.

Embodiments of the present disclosure are directed to antenna apparatuses including antenna systems designed for sending and/or receiving radio frequency signals to and/or from a satellite or a constellation of satellites.

The antenna systems of the present disclosure may be employed in communication systems providing relatively high-bandwidth, low-latency network communication via a constellation of satellites. Such constellation of satellites may be in a non-geosynchronous Earth orbit (GEO), such as a low Earth orbit (LEO). FIG. 1 illustrates a not-to-scale embodiment of an antenna and satellite communication system 100 in which embodiments of the present disclosure may be implemented. As shown in FIG. 1, an Earth-based endpoint or user terminal 102 is installed at a location directly or indirectly on the Earth's surface such as house or other building, tower, a vehicle (e.g., land-based vehicle, watercraft, aircraft, spacecraft, or the like), or another location where it is desired to obtain communication access via a network of satellites. An Earth-based endpoint terminal 102 may be in Earth's troposphere, such as within about 10 kilometers (about 6.2 miles) of the Earth's surface, and/or within the Earth's stratosphere, such as within about 50 kilometers (about 31 miles) of the Earth's surface, for example on a geographically stationary or substantially stationary object, such as a platform or a balloon.

A communication path may be established between the endpoint terminal 102 and a satellite 104. In the illustrated embodiment, the first satellite 104, in turn, establishes a communication path with a gateway terminal 106. In another embodiment, the satellite 104 may establish a communication path with another satellite prior to communication with a gateway terminal 106. The gateway terminal 106 may be physically connected via fiber optic, Ethernet, or another physical connection to a ground network 108. The ground network 108 may be any type of network, including the Internet. While one satellite 104 is illustrated, communication may be with and between any one or more satellite of a constellation of satellites.

The endpoint or user terminal 102 may include an antenna apparatus 200, for example, as illustrated in FIGS. 2A and 2B. As shown, the antenna apparatus 200 may include a housing assembly 202, which includes a radome portion 206 and a lower enclosure 204 that couples to the radome portion 206. As described below, the radome portion 206 may be a radome assembly 305 (See FIG. 3B). An antenna system and other electronic components, as described below, are disposed within the housing assembly 202. In accordance with embodiments of the present disclosure, the antenna apparatus 200 and its housing 202 may include materials for durability and reliability in an outdoor environment as well as facilitating the sending and/or receiving radio frequency signals to and/or from a satellite or a constellation of satellites with the satellites 104.

FIG. 2B illustrates a perspective view of an underside of the antenna apparatus 200. As shown, the antenna apparatus 200 may include a lower enclosure 204 that couples to the radome portion 206 to define the housing 202. In the illustrated embodiment, the mounting system 210 includes a leg 216 (a "mast") and a base (a "mount," not shown). The base may be securable to a surface and configured to receive a bottom portion of the leg 216. The leg 216, shown as a single mounting leg, may be defined by a generally hollow cylindrical or tubular body, although other designs and

shapes may be suitably employed. With a hollow configuration, any necessary wiring or electrical connections may extend into and within the interior of the leg 204 up into the housing 202 of the antenna apparatus 200.

A tilting mechanism 240 (details not shown) disposed within the lower enclosure 204 permits a degree of tilting to point the face of the radome portion 206 at a variety of angles for optimized communication and for rain and snow run-off. Such tilting may be automatic or manual.

Returning to FIG. 1, the antenna apparatus 200 is configured to be mounted on a mounting surface for an unimpeded view of the sky. As not limiting examples, the antenna apparatus 200 may be mounted at an Earth-based fixed position, for example, the roof or wall of a building, a tower, a natural structure, a ground surface, an atmospheric platform or balloon, or on a moving vehicle, such as a land vehicle, airplane, or boat, or to any other appropriate mounting surface having an unimpeded view of with the sky for satellite communication.

In various embodiments, the antenna apparatus 200 includes an antenna system designed for sending and/or receiving radio frequency signals to and/or from a satellite or a constellation of satellites. The antenna system, as described below, is disposed in the housing assembly 202 and may include an antenna aperture 208 (see FIG. 2A) defining an area for transmitting and receiving signals, such as a phased array antenna system or another antenna system. Besides the antenna aperture 208, the antenna apparatus 200 may include other electronic components within the housing assembly 202, for example, which may include, but are not limited to beamformers, a modem, a Wifi card and/or Wifi antennas, a GPS antenna, as well as other components.

Turning to FIG. 3A, the antenna apparatus 200 may include an antenna stack 250, an internal cover 252, a lower enclosure 204, and a tilting mechanism 240 coupled to a leg 216. The leg 216 may extend through an opening 254 defined by the lower enclosure 204 and may couple to the tilting mechanism 240. A volume 258 may be defined between the antenna stack 250 and the lower enclosure 240. The internal cover 252 may be coupled to the lower enclosure within the volume 258, forming an inner volume 256 between the internal cover 252 and the lower enclosure 204. The coupling between the internal cover 252 and the lower enclosure 204 may be waterproof or water resistant (e.g., the internal cover 252 may be hermetically sealed to the lower enclosure 204), and the opening 254 may be defined within the inner volume 256. In that regard, any debris or moisture that enters the inner volume 256 via the opening 254 may remain within the inner volume 256, reducing the likelihood of such debris or moisture reaching the remainder of the volume 258 (including the antenna stack 250).

The tilting mechanism 240 may be coupled to at least one of the lower enclosure 204 and the internal cover 252 such that rotation of the tilting mechanism 240 relative to the leg 216 results in rotation of the antenna stack 250 relative to the leg 216. Such rotation may be used to physically adjust of the position of the antenna aperture 208.

FIG. 3B illustrates an exploded view of the antenna stack 250, showing various layers of the antenna stack 250. In some examples, the antenna stack 250 may include a radome assembly 305 which may include a radome body assembly 310 and an outer layer 315. The antenna stack 250 may further include a patch antenna assembly 334 that includes an upper patch antenna layer 330, an antenna spacer 335, and a lower patch antenna layer 370 which together form a plurality of patch antennas forming an antenna array. The antenna stack 250 may also include a dielectric layer 375

and a printed circuit board (PCB) assembly **380**. As will be discussed further below, the various layers of the antenna stack **250** may be at least partially mechanically and/or electrically coupled together.

As shown in the illustrated embodiment, the layers of the antenna stack **250** may be rectangular in shape. That is, each of the radome assembly **305**, patch antenna assembly **334**, dielectric layer **375**, and PCB assembly **380** may have a rectangular shape when viewed from above or below (i.e., along a stacking axis of the antenna stack **250**). However, one skilled in the art will realize that the shape of the antenna stack **250** (and all elements therein) may have any shape such as rectangular, square, circular, oval, square, and the like, and may have any additional features such as rounded corners, sharp corners, and the like. As shown each element of the antenna stack **250** may have similar lengths and widths (as well as the lower enclosure **204**). As will be further discussed below, the radome assembly **305** may have a slightly greater length and a slightly greater width than the remaining elements of the antenna stack **250** to facilitate coupling of the radome assembly **305** to the lower enclosure **204** in such a manner to cause the remaining elements of the antenna stack **250** to remain wholly enclosed within the volume **258**. However, one skilled in the art will realize that the various layers may have different dimensions.

Radome Assembly

Referring to FIGS. **4A**, **4B**, and **5**, various additional features of the radome assembly **305** are shown. The radome assembly **305** can include a radome body assembly **310** that is coupled to an outer layer **315**. As seen in FIG. **5**, the radome body assembly **310** may extend from a first end **401** to a second end **403**, wherein the outer layer **315** may be located at or near the first end **401**, and second end **403** is located nearest the lower enclosure **204** when the antenna apparatus **200** is fully assembled (e.g., see exploded view in FIG. **3B**). In some embodiments, the radome body assembly **310** and the outer layer **315** may be referred to as a radome or a radome portion. The outer layer **315** may be exposed to the elements when the antenna apparatus **200** is fully installed and, thus, the outer layer **315** may include water or other weatherproofing features, as described in more detail below.

The radome assembly **305** is designed to be an outer portion of the antenna apparatus **200**, which is exposed to the outdoor environment and has mechanical properties of good strength to weight ratios, and a high modulus of elasticity for stiffness and resistance to deformation. Where referred to herein, discussion of the radome assembly **305** may refer to any one or more component of the radome assembly **305** such as at least one of an outer layer **315**, a radome body portion **402**, a radome spacer portion **404**, elongated members **400**, and the like. So as not to impede RF signals, the radome assembly **305** may be made from one or more materials having electrical properties of a low dielectric constant, and a low loss tangent through which antenna signals may travel. In addition, in some embodiments, the radome assembly **305** has chemical properties, for example, of bondability for bonding with adhesive, UV resistance, and low or near zero water absorption. The radome lay-up can also have other suitable properties to mitigate vulnerability to constant outdoor exposure and extreme weather conditions.

The radome assembly **305** is designed to maintain high mechanical values and electrical insulating qualities in both dry and humid conditions over thermal cycles between -40 degrees Celsius ($^{\circ}$ C.) and 85° C. In some embodiments, the radome assembly **305** has a relatively high yield strength

and a relatively high enough modulus to spread load on various portions of the radome assembly **305**. In some embodiments of the present disclosure, the radome assembly **305** has a dielectric constant of less than 4. In some embodiments of the present disclosure, the radome assembly **305** has a loss tangent of less than 0.001.

The radome body assembly **310** may include multiple portions, or components, which may be formed integrally or monolithically (e.g., from a same piece of material or collection of base materials and formed together) or, in various embodiments, may be formed separately and coupled together in any known manner. For example, the radome body assembly **310** may include any one or more of elongated members **400**, a radome body portion **402**, and a radome spacer portion **404**. As will be described in further detail below, the elongated members **400** may be used to couple the radome assembly **305** to additional layers of the antenna apparatus **200**. For example, an end portion **470** of the elongated members **400** (which may be located at the second end **403** of the radome body portion **402**) may extend through some or all layers of the antenna stack assembly **250** (see FIG. **3B** and FIG. **10**) and may be deformed or otherwise manipulated to resist separation of the various layers after assembly (e.g., see assembly of the antenna stack assembly **250** in FIG. **10**).

In some embodiments of the present disclosure, one or more components of the radome assembly **305** may be constructed of suitable materials, such as plastic with one or more properties of bondability for bonding with adhesive, UV resistance, and low or near zero water absorption.

The radome body portion **402** may include a planar surface that extends across an entire width **408** and length **410** of the radome body assembly **310**. The radome body portion **402** may have a rectangular shape, or may include any other shape such as circular, elliptical, square, or the like. The radome body portion **402** may provide structural support to the outer layer **315**, may at least partially protect additional elements of the antenna stack **250** (see FIG. **3B**) from elements in an environment of the antenna apparatus **200**, and may be formed from a material through which antenna signals may travel (e.g., the radome body portion **402** is designed for reduced interfere with antenna signals). The radome body portion **402** may have a planar top surface **412** and a uniform thickness **414** throughout. However, in various embodiments, the radome body portion **402** may have a curved top surface **412**, may have a non-uniform thickness, or the like.

The thickness **414** of the radome body portion **402** may be in the range of less than or equal to 60 thousandths of an inch (mil, 1.5 millimeters (mm)), less than or equal to 30 mil (0.76 mm), less than or equal to 20 mil (0.51 mm), or less than or equal to 10 mil (0.25 mm). The thickness may depend on the conditions of the environment in which the antenna apparatus **200** resides, for example, with a greater thickness **414** being used in geographic locations having harsh weather conditions, such as heavy rain and hail. However, a reduced thickness **414** may reduce radio frequency (RF) signal attenuation from the antenna array. In one embodiment, the radome body portion **402** has a thickness of 0.5 mm.

In some embodiments, the radome body portion **402** and the outer layer **315** (or the radome body assembly **310** and the outer layer **315**) may be formed together (integrally or monolithically) and be formed from the same or different materials. In other embodiments, the radome body portion **402** and the outer layer **315** (or the radome body assembly

310 and the outer layer 315) may be formed separately and assembled together from the same or different materials.

The radome spacer portion 404 may be made from the same or different material as the radome body portion 402 and may support the radome assembly 305 in providing mechanical and environmental protection to the antenna aperture 208 and other components of the antenna apparatus 200. The radome spacer portion 404 may also provide suitable spacing between the antenna elements of the antenna aperture 208 and the outer layer 315 of the radome assembly 305. As described in greater detail below, such spacing can provide advantages in reduced signal attenuation due to environmental effects on the outer top surface of the radome body portion 402, such as dirt, dust, moisture, rain, and/or snow.

In some embodiments, the radome spacer portion 404 is a plastic or foam layer having properties of low dielectric constant, low loss tangent, good compression strength, and a suitable coefficient of thermal expansion (CTE). In addition, the radome spacer portion 404 may have the property of bondability for bonding with adhesive for coupling with other layers in the antenna stack assembly 250.

As part of the radome assembly 305, the radome spacer portion 404 may also be designed to maintain high mechanical values and electrical insulating qualities in both dry and humid conditions over thermal cycling between -40°C . and 85°C . In some embodiments of the present disclosure, the radome spacer portion 404 has a dielectric constant of less than 1.0. In some embodiments of the present disclosure, the radome spacer portion 404 has a loss tangent of less than 0.001.

The radome body portion 402 may be adjacent or coupled to a radome spacer portion 404 to space the outer top surface 412 of the radome body portion 402 (or outer layer 315) from components of the antenna stack 250. In some embodiments, the radome body portion 402 may be formed together with the radome spacer portion 404 or formed separately and coupled to the radome spacer portion 404, for example, by adhesive bonding. As mentioned above, the radome body portion 402 and radome spacer portion 404 may together (alone or in combination with elongated members 400) be referred to as a radome body assembly 310. The radome spacer portion 404 may also have a planar and rectangular shape corresponding to that of the radome body portion 402 (see FIG. 4A).

As seen in FIG. 5 and in some embodiments, the radome spacer portion 404 may be thicker than the radome body portion 402. In accordance with embodiments of the present disclosure, the radome spacer portion 404 has a thickness such that the distance from the top patch antenna layer to the top of the radome assembly 305 is in the range of greater than about 3.0 mm, less than about 4.5 mm, or in the range of 3.0 mm to 4.5 mm.

The radome spacer portion 404 may include a spacing configuration to space the radome body portion 402 from the antenna aperture 208 with air. As one non-limiting example, the radome spacer portion 404 may be made from foam material having air disposed within the structure of the foam. Foam spacers may be advantageous materials in some environments because of their lower dielectric constant and lower thermal conductivity. For example, in cold environments (such as cold climates or for antenna apparatuses 200 disposed on airplanes) foam spacers may provide an insulative effect for electrical components). One suitable foam may be a polymethacrylimide (PMI) or a urethane foam. However, other foams are within the scope of the present

disclosure. Foams, unlike other materials described herein having thermal conductivity, may require separate heating systems for snow melt.

In other embodiments, the radome spacer portion 404 may be a frame structure. In one suitable embodiment, the frame structure may be designed to have air spaces within the structure of the plastic. One suitable frame structure may be a honeycomb structure. A suitable honeycomb structure may be made from a low-loss plastic material (such as thermoplastic or another suitable plastic material), which may be configured in a honeycomb frame construction.

In some embodiments, the radome spacer portion 404 may be air.

In some embodiments, the radome spacer portion 404 may include an interior portion 327 and an exterior portion 328 (see FIGS. 4A and 4B). In the illustrated embodiment, the interior portion 327 includes a plurality of cell walls 316, or cell portions 316, defining a plurality of apertures 315. The exterior portion 328 may extend around at least a portion of the outer perimeter of the interior portion 327 and may be a solid or continuous portion to assist in heat transfer around the outer perimeter of the antenna apparatus 200. In some embodiments, the exterior portion 328 may not be present. That is, inclusion of the exterior portion 328 may be optional.

Each of the plurality of cell walls 316 may extend away from the radome body portion 402. As seen in FIG. 5, the radome body portion 402 may have a first surface 412, or top surface, defining a planar surface at or near the first end 401 of the radome body assembly 310 and a second surface 413, or bottom surface, opposite the first surface such that each of the plurality of cell walls 316 extends away from the second surface 413 (and towards the second end 403 of the radome body assembly 310). Each of the plurality of cell walls 316 may include an opening (extending from a first end at or near the second surface 413 of the radome body assembly 310 to the second end toward the second end 403 of the radome body assembly 310), and a vertical pathway therebetween defining an aperture 317. Each aperture 317 is configured to vertically align with an individual antenna element in the antenna array to provide an airspace above each upper patch element of each antenna element in the antenna array. The cell structure is configured to provide uniform spacing around each antenna element.

A group of cell walls 316 and a single aperture 317 within the plurality of cell walls may together form a cell. In that regard, each cell in the embodiment shown in FIGS. 4A-5 may include 6 cell walls 316 and a single aperture 317 (e.g., a single cell 450 shown in FIG. 4B may include cell walls 451a-451f and a single aperture 452). In some embodiments, at least a portion of the cell walls 316 may at least partially define an adjacent aperture 317 of an adjacent cell. For example, the cell wall 451b may at least partially define a cell 456. One skilled in the art will realize that the cell walls 316 may have any shape (e.g., rounded, straight, angled, or combinations thereof), and that a cell may include any quantity of cell walls 316 (including a single cell wall 316 defining a single cell), without departing from the scope of the present disclosure.

In some embodiments, at least two cell walls 316 (or cell portions 316) defining a cell may be spaced apart from each other. For example, any two or more of the cell walls 451a-451f defining the cell 450 may be spaced from each other (e.g., cell wall 451a may be spaced apart from cell wall 451d). In some embodiments, any two or more adjacent cell walls 316 defining a cell may be spaced apart from each other. For example, the cell wall 451A may be spaced apart

from adjacent cell wall 451B by a gap 453. Such spacing between cell walls 316 defining a cell may be referred to as a nodeless cell configuration. The spacing between cell walls 316 can provide advantages in manufacturing and/or may provide advantages during use. For example, the spacing can enable venting between adjacent cells, which may provide pressure equalization during heat cycling.

As referenced above, cell walls 316 may have any shape. In such embodiments any two cell portions, or cell walls 316, defining a cell may be spaced apart from each other. For example, if cell portions include two semicircular walls defining a cell then at least one intersection of the two semicircular walls may be spaced apart from each other. In that regard, each cell may have at least one gap defined by the cell walls 316 that form the cell.

In the illustrated configuration three cell walls 316 come together to define gap 453. In other configurations four or other numbers of cell walls could come together to define a gap 453.

The cell walls 316 of the interior portion 327 may provide a greater proportion of air to mitigate any RF interference with antenna signals from the antenna array 308. In some embodiments, the volumetric ratio of air to solid surface area or the cell 315 of the radome spacer 310 is greater than about 50:50, or alternatively greater than about 65:45, or alternatively greater than about 75:25, or alternatively greater than about 80:20, or alternatively greater than about 85:15, or alternatively greater than about 90:10.

As described above, one or more components of the radome assembly 305 may be formed from a plastic or other polymer. For example, the one or more components of the radome body assembly 310 may include polypropylene (PP), polycarbonates, polybutylene terephthalate (PBT), polyphenylene ether (PPE), poly(p-phenylene oxide) (PPO), polystyrene (PS), polyethylene terephthalate (PET), polyvinyl chloride (PVC), liquid crystal polymer (LCP), other polymers, or mixtures thereof.

In some embodiments of the present disclosure, one or more components of the radome assembly 305 may include a lay-up made from a first layer made from fibrous material, such as fiberglass or Kevlar fibers, preimpregnated with a resin, such as an epoxy or polyethylene terephthalate (PET) resin.

In some embodiments, one or more components of the radome assembly 305 may have a fiberglass base for mechanical strength. The fiberglass may be laminated with a polymer or copolymer of polyethylene.

In some embodiments, the radome assembly 305 may include one or more components formed from a plastic with a plurality of fibers located throughout. For example, the fibers may include fiberglass, Kevlar fibers, carbon fibers, or the like.

One or more components of the radome assembly 305 may include fiberglass-reinforced epoxy laminate material, such as FR-4 or NEMA grade FR-4. In other embodiments, the radome assembly 305 may include another type of high-pressure thermoset plastic laminate grade, or a composite, such as fiberglass composite, quartz glass composite, Kevlar composite, or a panel material, such as polycarbonate.

As described in greater detail below, the radome assembly 305 may include a hydrophobic surface for water removal. For hydrophobic properties, one or more components of the radome assembly 305 may be functionalized with fluorine and/or chlorine. For example, a suitable material may include a fluorinated polymer (fluoro polymer), such as

polytetrafluoroethylene (PTFE) or a copolymer of ethylene and chlorotrifluoroethylene, such as ethylene chlorotrifluoroethylene (ECTFE).

Radome Outer Layer

The radome assembly 305 may include an outer layer 315. RF signal attenuation due to gain degradation can be significant as a result of rain or moisture accumulation on the first end 401 of the radome assembly 305, and the outer layer 315 may assist in reducing or eliminating such concerns. Regarding rain and moisture accumulation, water has a significant relative permittivity which can introduce a non-trivial interface for an antenna aperture causing RF reflection. Such RF reflection results in gain degradation in the RF signal.

Snow accumulation on the first end 401 of the radome assembly 305 was generally not found to be as degrading to the RF signal power as water accumulation. However, snow having moisture content was found to be degrading, such as snow at or near 0° C., or melting snow or ice resulting in water accumulation on the on the first end 401 of the radome assembly 305 was found to significantly degrade the RF signal power.

As described above, to mitigate signal attenuation due to the lingering presence of droplets of rain, the outer layer 315 (and the radome body portion 402) may be spaced a predetermined distance from the antenna aperture 208 defined by the array of antenna elements. In accordance with embodiments of the present disclosure, the radome spacer portion 404 provides a suitable thickness to space the outer surface 315 (and potentially the radome body portion 402) a predetermined distance from the upper patch layer of the antenna aperture 208. As described above, in one embodiment of the present disclosure, an outer surface of the outer layer 315 is equidistantly spaced from the upper patch antenna element of each individual antenna element in the antenna aperture at a distance of at least 3.0 mm.

For moisture mitigation and to aid in the run-off of water or moisture accumulating on the radome assembly 305, the outer layer 315 may include a hydrophobic or superhydrophobic material having low surface energy to cause water to bead up and not spread out.

In addition to a hydrophobic or superhydrophobic outer layer 315, tilting of the antenna apparatus 200 (see FIG. 2A) may help to mitigate snow and moisture accumulation.

When formed separately, the outer layer 315 may be coupled to the radome body assembly 310 using any known technique. For example, as discussed above, the outer layer 315 may be bonded to the radome body assembly 310 using an adhesive. The adhesive may include any adhesive such as a pressure sensitive adhesive (PSA) applied to a surface of the outer layer 315. In that regard, the PSA may be placed in contact with the outer layer 315 and the radome body portion 402 and pressure may be applied to the outer layer 315 to couple the outer layer 315 to the radome body assembly 310. In some embodiments, the adhesive may include an epoxy, heat activated adhesive, or any other adhesive in the art.

In some embodiments, the outer layer 315 may be a thin sheet that is applied to the upper surface of the radome body assembly 310. Either the outer layer 315 or the radome body assembly 310 may be activated on its bonding surface for bonding with an adhesive, such as a pressure sensitive adhesive. Suitable activation may include sodium etching, plasma treatment, corona treatment, or other suitable activation treatments to create bonding sites. The outer layer and/or adhesive lay-up can be routed into a desired shape.

In some embodiments, the outer layer **315** may be formed to include a UV blocker, which may protect the adhesive (e.g., the pressure sensitive adhesive). In some embodiments, the radome body assembly **310** may include a UV blocker in the form of pigmentation. For example, the outer layer **315** and/or the radome body assembly **310** may include titanium dioxide (TiO₂) for UV blocking.

In other embodiments, the outer layer **315** may be formed by melting a separate material and adding it to the radome body assembly **310**, may be molded (e.g., insert molding), painted, sprayed, and the like. In some embodiments, the outer layer **315** may be applied to the radome body assembly **310** using a spray or roll-on technique (e.g., by spraying or rolling on a liquid or gaseous phase of the outer layer material). In some embodiments, a melted outer layer **315** may be applied to the radome body assembly **310** and allowed to dry-harden in place.

In some embodiments, the outer layer **315** may be formed to have greater dimensions (e.g., length and width) than those of the radome body portion **310**. In such embodiments, the outer layer **315** may be applied to the radome body portion **310** and then cut (e.g., die cut) to have the same dimensions as the radome body portion **310**.

In some embodiments, the outer layer **315** may have a thickness **416** that is less than or equal to 20 mil (0.51 mm), less than or equal to 10 mil (0.25 mm), less than or equal to 5 mil (0.13 mm), less than or equal to 3 mil (0.076 mm), less than or equal to 1 mil (0.025 mm), or the like.

Antenna Layers

FIG. 3B illustrates an exemplary antenna apparatus **200** with an exemplary antenna stack assembly **250** in the form of a plurality or stack of layers. The illustrated plurality of layers includes layers of spacers or spacer portions positioned against other layers including antenna layers or layers including antenna elements or components, which may be for instance electronic layers, such as printed circuit board (PCB) layers.

In the illustrated embodiment of FIG. 3B, the layers in the antenna stack assembly **250** layup include a radome assembly **305**, a patch antenna assembly **334**, a dielectric layer **375**, and a printed circuit board (PCB) assembly **380**.

As illustrated in FIG. 3B, an outer top layer of the antenna stack assembly **250** is an outer layer **315** of the radome assembly **305**. As described above, in the illustrated embodiment, the radome assembly **305** can include the radome body assembly **310** and the outer layer **315**.

In the illustrated embodiment of FIG. 3B, a patch antenna assembly **334** is a phased array antenna assembly made up from a plurality of individual patch antenna elements **304** (see FIGS. 7A and 7B) configured in an array **308**. (See FIG. 6A for a top view of an array of upper patch antenna elements **330a**). A patch antenna is generally a low-profile antenna that can be mounted on a flat surface, including a first flat sheet (or "first patch") of metal mounted over, but spaced from, a second flat sheet (or "second patch") of metal, the second patch defining a ground plane. The two metal patches together form a resonant structure. The individual patches may be formed using known metal deposition techniques on a standard PCB layer or other suitable substrate. In an alternate embodiment, the patches may be printed, for example, using a conductive ink, on the patch layers. An array of multiple patch antennas on the same substrate can be used to make a high gain array antenna or phased array antenna for which the antenna beam can be electronically steered.

FIG. 7A illustrates a perspective view of a simplified exemplary individual antenna element **304** including an

upper patch layer **330a**, a lower patch layer **370a**, and spacing therebetween. The individual element **304** shown FIG. 7A is one of a plurality of antenna elements **304** forming an array of antenna elements (see FIG. 6A).

In the illustrated embodiment, the array **308** of individual patch antenna elements **304** is formed from a plurality of patch antenna layers, including the upper patch antenna layer **330** (see also FIG. 6A), the antenna spacer **335** (see FIG. 6B), and the lower patch antenna layer (or ground plane) **370** (see FIG. 6C). As mentioned above, the upper antenna patch layer **330** and the lower patch antenna layer **370** may be formed on standard PCB layers or other suitable substrates. The two layers **330** and **370** are suitably spaced from each other specific by the antenna spacer **335** to achieve the desired tuning of the patch antenna assembly **334**. While a two-patch (upper and lower patch) antenna is illustrated herein, other single or multilayer patch antennas may be employed in accordance with embodiments of the present disclosure.

As seen in FIG. 3B, the radome assembly **305** is positioned adjacent the upper patch layer **330** to protect the upper surface of the upper patch layer **330**. FIG. 6A illustrates a top view of the upper patch layer **330**. As seen in FIG. 6A, the upper surface of the upper patch antenna layer **330** includes an interior portion **347** having a plurality of individual upper antenna patch elements **330a** that make up the upper patches of individual antenna elements **304** defining the antenna array **308**. The upper antenna patch elements **330a** may be a plurality of discrete individual dots, circles, modified circles, or other polygonal shapes made up of a conductive metal such as copper. The upper antenna patch elements **330a** may be separated from each other on the upper patch layer **330** by non-conductive portions of the upper patch antenna layer **330** between the upper antenna patch elements **330a**.

The upper patch antenna layer **330** further includes an exterior portion **349** extending to its perimeter. The exterior portion **349** may be relatively small (e.g., may include a relatively small fraction of the entire surface area of the upper patch antenna layer **330** such as 1 percent, 3 percent, 5 percent, 10 percent, or the like), or in some embodiments, the upper patch antenna layer **330** may include no exterior portion. The exterior portion **349** may be configured to port or flow thermal energy (heat) radially from the overall antenna stack assembly **250** outward to the perimeter of the upper patch layer **330** and to the perimeter of the radome assembly **305**.

The upper patch layer **330** may define ports **332** through which the elongated members **400** of the radome body assembly **310** (see FIG. 5) may pass. The ports **332** may be located between upper patch antenna elements **330a**, so as to not interfere with any antenna elements **304** of the antenna array. The ports **332** may be formed during molding or other formation of the upper patch antenna layer **330**, may be cut or drilled into a pre-formed upper patch antenna layer **330**, or the like. The elongated members **400** of the radome body assembly **310** engage the PCB assembly **380** (see FIG. 10). The upper patch antenna layer **330** may also port or flow heat to the ports **332** where the elongated members **400** port the heat to the radome body assembly **310**, which can be used to not only dissipate unwanted heat from electrical components attached to the PCB assembly **380**, but also such heat can be repurposed to mitigate snow and rain accumulation on the outer surface **315** of the radome assembly **305**.

In some embodiments, the upper patch antenna layer **330** is a PCB substrate having a plurality of upper antenna patch

elements **330a**. The features of the upper patch antenna layer **330** may be formed by suitable semiconductor processing to obtain the desired feature patterns and shapes.

Turning to FIGS. 3B and 6B, the lower patch antenna layer **370** may be spaced from the upper patch antenna layer **330** by an antenna spacer **335**. The antenna spacer **335** may include a plurality of cell walls **336** that define a plurality of open cells **337**. The antenna spacer **335** may also define a plurality of ports **331a** extending therethrough. The ports **331a** may be aligned with ports defined by other layers of the antenna stack **250** and with the elongated members **400** of the radome body assembly **310**. In that regard, the elongated members **400** may extend through the ports **331** to couple the layers of the antenna stack **250** together (see FIG. 10). Because the antenna spacer **335** includes only cell walls **336** in an interior portion of the antenna spacer **335**, ports **331b** may be defined at junctions of cell walls **336**. That is, certain cell walls **336** may not intersect with adjacent cell walls to form the ports **331b**. The ports **331a** and **331b** may be formed during molding or other formation process of the antenna spacer **335**, may be cut or drilled into a pre-formed antenna spacer **335**, or the like.

Each of the plurality of cell walls **336** may extend substantially parallel to a stacking axis of the antenna stack assembly **250**. The cells **337** of the antenna spacer **335** may have a similar shape as the cells **315** defined by the cell walls **316** of the radome spacer portion **404**. In some embodiments, the cells **337** may have a different shape such as circular, oval, square, or any other shape. Each of the cells **337** may align with an antenna element **304**. The cells **337** may each define a vertical pathway **338** extending along an entire thickness of the antenna spacer **335**. That is, the pathway **338** may include a void extending through from a first side to a second side of the antenna spacer **335** such that the antenna spacer **335** lacks any material directly aligned with the antenna elements **304** along the stacking axis.

A group of cell walls **336** and a single pathway **338** within the plurality of cell walls may together form a cell **337**. In that regard, each cell **337** may include 6 cell walls **336** and a single pathway **338**. In some embodiments, at least a portion of the cell walls **336** may at least partially define an adjacent pathway **338** of an adjacent cell **337**. One skilled in the art will realize that the cell walls **336** may have any shape (e.g., rounded, straight, angled, or combinations thereof), and that a cell **337** may include any quantity of cell walls **336** (including a single cell wall **336** defining a single cell), without departing from the scope of the present disclosure.

The cell height of the antenna spacer **335** may be in the range of 1 mm to 2 mm (e.g., about 1.2 mm). Likewise, the cell walls **336** of the antenna spacer **335** may be in the range of 1 mm to 2 mm wide (e.g., about 1.2 mm).

A suitable plastic for the antenna spacer **335** may be thermally conductive and capable of dissipating heat through its structure, while also have a low dielectric constant. In one embodiment of the present disclosure, the antenna spacer **335** may be made from the same or similar materials as the radome body assembly **310** and may have a dielectric constant of less than 3.0, and a thermal conductivity value of greater than 0.35 W/m-K or greater than 0.45 W/m-K.

The antenna spacer **335** may be made up of the same or similar materials and by similar manufacturing processes as the radome spacer **310**. As seen in FIG. 6B, the antenna spacer **335** may have a honeycomb structure, similar to the radome spacer portion **404** or may be made from a suitable foam or other suitable spacing structure. Although illustrated and described as a single spacing layer, the antenna spacer

335 may be comprised of a plurality of spacer elements defining the space between the upper and lower patch layers **330** and **370** of the patch antenna assembly **334**.

Referring to FIGS. 3B and 6C, the lower patch antenna layer **370** is spaced by antenna spacer **335** from the upper patch antenna layer **330**. As shown, a top surface **372** of the lower patch antenna layer **370** includes a plurality of individual upper antenna patch elements **370a** that make up the lower patches of individual antenna elements **304** defining the antenna array **308**. Like the upper antenna patch elements **330a**, the lower antenna patch elements **370a** may be a plurality of discrete individual dots, circles, modified circles, or other polygonal shapes made up of a conductive metal such as copper. The lower antenna patch elements **370a** may be separated from each other on the lower patch layer **370** by portions of the lower patch antenna layer **370** between the lower antenna patch elements **370a**. In one embodiment, the lower patch antenna layer **370**, like the upper patch antenna layer **330**, is a PCB substrate having a plurality of upper antenna patch elements **370a**.

The lower patch antenna layer **370** may also define ports **333** extending from the top surface **372** to a bottom surface **373**. As with ports defined by other layers of the antenna stack **250**, the elongated members **400** of the radome body assembly **310** may extend through the ports to couple the layers together (see FIG. 10). The ports **333** may be located between lower patch antenna elements **370a** such that the elongated members **400** fail to interfere with operation of the various lower patch antenna elements **370a**. The ports **333** may be formed with the lower patch antenna layer **370** during molding or other formation of the lower patch antenna layer **370**, may be cut or drilled into a pre-formed lower patch antenna layer **370**, or the like.

As seen in FIG. 7A, the individual lower patch layer elements **370a** are configured to align with the individual upper patch antenna elements **330a**, for example, in a vertical stack. The lower patch antenna elements **370a** may be the same as or similar in shape and configuration as the upper patch antenna elements **330a**. In the illustrated embodiment, the upper patch elements **330a** are generally circular in configuration and include a plurality of slots for antenna polarization or tuning effects, while the lower patch antenna elements **370a** are generally circular in configuration.

As seen in FIG. 7B, the upper patch antenna layer **330** is spaced by an antenna spacer **335** from the lower patch antenna layer **370**. As described above, the antenna spacer **335** may be made up of the same or similar material as the radome spacer portion **404** (and, by extension, may include the same material as the entire radome body assembly **310**), and may also have a cell and wall structure similar to that of the radome spacer portion **404**. Similar to the upper patch antenna elements **330a** and the radome spacer portion **404**, each of the plurality of apertures in the antenna spacer **335** may include a vertical pathway to align with each lower patch element **370a** (at the bottom) and each upper patch antenna element **330a** (at the top) to define a plurality of individual antenna elements **304** in the antenna array **308**.

Referring to FIG. 3B, below the lower antenna patch elements **330a** and **370a** is the PCB assembly **380**, which includes circuitry that may be aligned with the upper and lower antenna patch elements **330a** and **370a**, which together may form a resonant antenna structure. The PCB assembly **380** is separated from the lower patch antenna **370** by a dielectric spacer **375**.

Dielectric Spacer

Referring to FIGS. 3B, 8A, and 8B, a dielectric layer 375 provides an electrical insulator between the patch antenna assembly 334 and the PCB assembly 380 and spaces the patch antenna assembly 334 from the PCB assembly 380. The dielectric layer 375 may have a low dielectric constant (which may be referred to as relative permittivity), for instance in the range of about 1 to about 4 at room temperature.

In accordance with embodiments of the present disclosure, in addition to being an electrical insulator, the dielectric spacer 375 may be configured to be a fire enclosure for the antenna apparatus 200. In that regard, the dielectric spacer 375 may be manufactured to have flame retardant properties, for example, by inclusion of 5% decabromodiphenyl ethane (DBDPE) together with the dielectric materials of the dielectric spacer 375.

The dielectric spacer 375 may include a planar body formed from a dielectric material 500 with a plurality of holes 502 formed therethrough. The material 500 of the dielectric spacer 375 may include any dielectric material. For example, the dielectric spacer 375 may include a polymer, silicon, or any other material or materials.

The holes 502 formed in the dielectric spacer 375 may optimize a scan angle of the antenna apparatus 200 (because the antenna apparatus 200 is a phased array antenna, it is capable of scanning in multiple directions). For example, the combination of the material 500 and the holes 502 (including the shape, size, and location of the holes 502) may increase a scan angle (i.e., an angle at which a main beam may form relative to the stacking axis of the antenna stack 250) by at least 0.5 percent, by at least 1 percent, by at least 1.5 percent, by at least 2 percent, by at least 2.5 percent, by at least 3 percent, or the like. In experiments, the dielectric spacer 375 shown herein achieved improvements in scan angle of at least 2 percent.

The holes 502 may have any shape. For example, the holes 502 may be circular, oval, triangular, square, rectangular, or any other polygonal or other shape. The holes 502 may have a diameter 504. In some embodiments, the diameter 504 may be between 1 millimeter and 25 millimeters (40 mil and 984 mil), between 2 millimeters and 15 millimeters (80 mil and 591 mil), between 3 millimeters and 10 millimeters (120 mil and 400 mil), or about 5 millimeters (197 mil).

In some embodiments, the holes 502 may be located around an individual antenna element 304 (e.g., around an individual upper patch antenna element 330a and lower patch antenna element 370a). That is, a group of holes 508 in the material 500 of the dielectric spacer 375 may encircle or surround a portion 510 of solid dielectric material 500. The holes 502 may surround portions 510 such that each portion 510 aligns with a different antenna element 304 such that solid dielectric material 500 is aligned with each antenna element 304 along the stacking axis (shown in detail in FIG. 8B). In some embodiments, the holes 502 may align with the gaps 453 between adjacent cell walls 316 of the radome spacer portion 404. This orientation of holes 502 aids in achieving the desired properties of the dielectric spacer 375 (i.e., the CTE value, the dielectric value and properties, the scan angle improvement, and the like).

As shown in FIG. 8B, each of the plurality of antenna elements 304 of the upper patch layer 330 align with each of the plurality of apertures 315 having the cell walls 316 of the radome spacer 310 and with openings of cells 337 defined by the antenna spacer 335. For example, each of the antenna elements 304 are disposed within the apertures 315 and the

cells 337 of the antenna spacer 335 to provide suitable spacing around each of the antenna elements 304.

At least some of the holes 502 of the dielectric spacer 375 may align with the ports 331, 332, 333 of the upper patch antenna layer 330, the antenna spacer 335, and the lower patch antenna layer 370. In that regard, the elongated members 400 may extend through the at least one of each port 331, 332, 333 and at least one hole 502 to couple the layers of the antenna stack 250 together.

The material 500 of the dielectric layer 375 may have a thickness 506. The thickness 506 may be, for example, between 0.1 mm and 5 mm (3.9 mil and 197 mil), between 0.2 mm and 2 mm (7.9 mil and 79 mil), between 0.5 mm and 1 mm (20 mil and 39 mil), or about 0.7 mm (28 mil). These thicknesses 506 may aid in achieving the desired properties of the dielectric spacer 375.

In some embodiments, the dielectric spacer 375 may include any other shape of holes so long as material 500 is aligned with the antenna elements 304. In some embodiments, the dielectric spacer 375 may lack holes or openings. In some embodiments, holes or openings may be aligned with the antenna elements 330a, 370a along the stacking axis. In some embodiments, the dielectric spacer 375 may include pucks, disks, or other separated pieces of dielectric material that is aligned with the individual antenna elements 304. In some embodiments, a plurality of pucks, disks, or other pieces of dielectric material may be coupled together, e.g., via wires, strips of material, or the like, to form the dielectric spacer 375. The advantageous features of the dielectric spacer 375 may be achieved by using a dielectric material (e.g., of the composition described above) aligned with the individual antenna elements 304 along the stacking axis; and voids, or a lack of dielectric material, at other locations on the same plane as the dielectric material.

The combination of materials described above forming the dielectric material 500 along with the holes 502 (including the shape, size, and location thereof) may together achieve a desirable set of characteristics or parameters of the dielectric spacer 375. In particular, the combination of materials used and holes 502 may provide a desirable CTE and a desirable dielectric constant which may be unavailable for commercial purpose. At least one of the CTE values and dielectric values allow the dielectric spacer 375 to achieve desirable beamforming capabilities and steering of the antenna apparatus 200, as well as a desirable signal-to-noise (SNR) ratio for received signals. For example this combination may provide a layer having a dielectric constant of between 1 and 5, between 1 and 4, between 2 and 4, between 2.5 and 3.5, or about 2.8; and a CTE of between 10 and 30, between 15 and 25, between 17 and 23, or about 20. In an exemplary embodiment, the dielectric spacer 375 may have a dielectric constant of about 2.8 and a CTE of about 20. As referenced above, materials are unavailable for commercial purpose with these properties.

PCB Assembly

In some embodiments and as shown in FIG. 3B, the patch antenna assembly 334 may be mechanically and electrically supported by a printed circuit board (PCB) assembly 380. The PCB assembly 380 is generally configured to connect electronic components using conductive tracks, pads and other features etched from one or more sheet layers of copper laminated onto and/or between sheet layers of a non-conductive substrate. The PCB assembly 380 may be a single or multilayer assembly with various layers including copper, laminate, substrates, and the like, and may have various circuits formed therein.

Referring to FIGS. 3B, 8B, 9A, 9B, and 9C, the PCB assembly 380 may have a first side 383 that faces and contacts the dielectric spacer 375 and a second side 384 opposite the first side 383. The PCB assembly 380 may include a plurality of electronic components 382 coupled thereto, such as microchips, processors, signal processors, beamforming logic devices, power modules, GPS receivers, resistors, capacitors, inductors, transistors, memory devices, and the like. Because the first side 383 faces the dielectric spacer 375 and the electronic components 382 may extend away from the PCB assembly 380, it may be undesirable for such electronic components 382 to be located on the second side 384 of the PCB assembly 380. Due to the lack of electronic components on the first side 383, the first side 383 may be in contact with and lie flush with the dielectric spacer 375. Additional electronic components (such as signal traces or other logic devices) may be located within the layers of the PCB assembly 380 so long as they avoid extending outward from the first side 383. In that regard, thermal energy generated by, or dispersed by, the PCB assembly 380 may travel away from the PCB assembly 380 to the dielectric spacer 375.

The PCB assembly 380 may define or include a plurality of ports 381 extending through the first side 383 and the second side 384. The ports 381 may be aligned with the ports 331, 332, 333 of the antenna layers and some holes 502 of the dielectric spacer 375. In that regard, the elongated members 400 of the radome assembly 305 may extend through the ports 381 of the PCB assembly to couple the radome assembly 305 to the PCB assembly 380 and, thus, coupling the layers of the antenna stack assembly 250 together (see FIG. 10).

Coupling of Antenna Stack Assembly

In some embodiments, the layers of the antenna stack 250 may be coupled together using mechanical fasteners. In particular and as shown in FIGS. 4B and 10, the radome body assembly 310 may include a plurality of elongated members 400 extending in a direction away from the radome body portion 402. As discussed in more detail below, the elongated members 400 can be utilized to couple together the layers of the antenna stack assembly 250. In another examples, the layers of the antenna stack 250 can be coupled together through an elongated member 800, as illustrated in FIG. 12.

As illustrated in FIGS. 4B, 5, and 10 the elongated members 400 can include a body 460 that extends from the radome body portion 402. The body 460 can define a first end portion 468 at or near the radome body portion 402 and a second end portion 470 distal from the radome body portion 402. The elongated members 400 can have two states. As shown in FIG. 5, the elongated member 400 is in a first state, where the body 460 forms a narrow profile. As shown in FIG. 10, the elongated member 400 is in a second state, where the end portion 470 of the body 460 forms a wide profile. When in the first state, the elongated member 400 can be received within the ports or holes (e.g., port 331, port 331, port 333, hole 502, and port 381) formed within the various layers of the antenna stack assembly 250 and thereby defining a thru-hole 472 there through. In that regard, the width of the body 460 in the first state is less than the width of the ports. (See FIG. 5.) In contrast, as shown in FIG. 10, when the elongated member 400 is in the second state, the end portion 470 of the body 460 can be wider than the width of the ports defining the thru-hole 472, which prevents the elongated member 400 from moving through the ports when in the second state.

As will be discussed in more detail below, the elongated members 400 can transition from the first state to the second state to couple the layers of the antenna stack assembly 250 together. For example, the elongated members 400 can be received within the ports of the antenna stack assembly 250 when in the first state and can then transition to the second state to interlock the layers of the antenna stack assembly 250 together.

Each of the layers of the antenna stack 250 may have openings, apertures, or ports that each align in the direction of the stacking axis with at least one of the elongated members 400 (or the elongated members 800) in response to each of the layers being aligned for assembly. For example, the upper patch antenna layer 330 defines ports 332, the antenna spacer 335 defines ports 331, the lower patch antenna layer 370 defines ports 333, the dielectric layer 375 defines holes 502, and the PCB assembly 380 defines ports 381. Each of the ports 332, 331, 333, 381 and holes 502 may align vertically, or along the stacking axis, with the elongated member 400.

In some embodiments, some or all of the openings may serve multiple purposes. For example, the ports 331 in the antenna spacer 335 may also operate as cell centers (e.g., be surrounded by cell walls of the antenna spacer 335) such that additional openings beyond the cells are unnecessary. Likewise, the holes 502 of the dielectric layer may also operate as the openings formed therein that align with the antenna elements 304. In some embodiments, at least some ports 331 in the antenna spacer 335 may be formed separate from the cell centers. In some embodiments, at least some holes 502 in the dielectric layer 375 may be formed separate from the other openings of the dielectric layer 375 (e.g., to avoid an elongated member 400 extending through an antenna element). In that regard, the antenna spacer 335 may be designed to facilitate alignment of the ports 331 and the cell centers or to avoid alignment of the ports 331 and the cell centers. Similarly, the dielectric layer 375 may be designed to facilitate alignment of the functional openings and the fastening holes 502 or to avoid alignment of the functional openings and the fastening openings 502.

In order to couple the layers of the antenna stack assembly 250 together, the layers may be stacked in order (e.g., with the radome assembly 305 at one end and the PCB assembly 380 at the other, with the remaining layers stacked in the same configuration shown in FIGS. 3B and 10) in such a manner that the elongated members 400 (or the elongated members 800) extend through a combined thru-hole 472 extending through the openings of the respective layers. In particular, the elongated members 400 may extend through the openings of the layers in the following order (starting from the closest opening to the radome body assembly 310): 332, 331, 333, 502, 381. It should be appreciated, however, that different orders are within the scope of the disclosure and that the antenna stack may include all or only some of the exemplary components described. The elongated members 400 may each include a proximal end at or near the radome body portion 402 and a distal end opposite the proximal end (where the distal end extends away from the radome body portion 402). Stated differently, the proximal end of the elongated members 400 may be coupled to the radome body assembly 310 (such as the radome body portion 402, the radome spacer portion 404, or the like).

In the illustrated embodiment of FIG. 10, the elongated members 400 extend through each of the openings 332, 331, 333, 502, 381, collectively defining a thru-hole 472 through the antenna stack 250) and the distal end portion 470 may be deformed (e.g., transitioned from the first state to the second

state), as discussed further below, to resist removal of the distal end portion 470 from the openings 332, 331, 333, 502, 381. In the illustrated embodiment of FIG. 10, in the second state, a shoulder forms 474 at the distal end portion 470 of each elongated member 400 to prevent the end portion 470 from disengaging from the thru-hole 472 of the antenna stack 250.

The layers may be pressed together using any known technique such as manual pressing, mechanical pressing, use of a vice, or the like. In some embodiments, the pressing may continue until the coupling is complete, may only occur until the layers are in the desired configuration, or for any duration therebetween.

While the layers are pressed together and the elongated members 400 extend through the thru-holes 472 of the antenna stack 250, end portions 470 of the elongated members may be warped or otherwise deformed. For example, the end portions 470 may be heated and reshaped manually or with equipment, may have pressure applied thereto for reshaping, or the like. The end portions 470 may be manipulated such that a dimension 610 of the end portion 470 in a direction parallel to a plane formed by the PCB assembly 380 is greater than a diameter 612 of the port 381 of the PCB assembly 380. The end portion 470 may be manipulated in such a way that the dimension 610 that is greater than the diameter 612 is at a location adjacent to (i.e., within 1 mil (0.0254 mm), 10 mils (0.254 mm), 100 mils (2.54 mm), 300 mils (7.62 mm), or the like) a plane defined by the PCB assembly 380 while the layers are pressed together.

After hardening of the end portion 470, the elongated members 400 couple the entire antenna stack assembly 250 (see FIG. 3B) from the radome body assembly 310 to the PCB assembly (due to the dimension 610 of the end portion 470 being greater than the diameter 612 of the port 381 while the layers are stacked together). Thus, the elongated members 400 may resist separation of the radome body assembly 310 from the remaining layers of the antenna stack assembly in the direction of the stacking axis and may also resist separation of the PCB assembly 380 from the remaining layers of the antenna stack assembly in the direction of the stacking axis. Because the elongated members 400 also extend through openings of the remaining layers, and the remaining layers are sandwiched between the radome body assembly 310 and the PCB assembly 380, the elongated members 400 also resist separation of any one of the layers from any other of the layers. Furthermore, because the elongated members 400 extend through openings defined by each layer of the antenna stack assembly 250, the elongated members 400 also resist separation of any layer from any other layer in directions parallel to the plane defined by surfaces of the layers.

The elongated members 400 can also couple the outer layer 315 to the remaining layers of the antenna stack assembly 250. Although the outer layer 315 of the radome assembly 305 may not be interlocked between the remaining layers via the elongated members 400, the outer layer 315 may be bonded to the radome body portion 402 using an adhesive (e.g., pressure-sensitive adhesive) or any other mechanism (e.g., other types of bonding such as chemical bonding). Therefore, the adhesive of the outer layer 315 and the interaction between the elongated members 400 and the openings may sufficiently couple each layer of the antenna stack assembly 250 together without use of any additional adhesive. In some embodiments, adhesive, fasteners, or other coupling means may be used to couple two or more layers of the antenna stack assembly 250 together. In some embodiments, the outer layer 315 may be coupled to the

radome body portion 402 in any manner in addition to, or instead of, the adhesive. For example, another fastener (e.g., screw, bolt, snap-fit connector, clip, or the like) may be used to fasten or couple the outer layer 315 to the radome body portion.

In some embodiments, the PCB assembly 380 may include electronic components 650 (e.g., semiconductor processors, memory chips, global positioning system (GPS) sensors, or the like) located on, and coupled to, the PCB assembly 380. In some embodiments, the components 650 may be located on a bottom surface (e.g., a surface facing away from the remaining layers of the antenna stack assembly 250) due to potential direct contact between a top surface of the PCB assembly 380 (e.g., opposite the bottom surface) and the dielectric layer 375. In that regard, the components 650 may remain coupled to the antenna stack assembly 250 due to the coupling of the components 650 to the PCB assembly 380.

As illustrated in FIG. 12, in an alternate embodiment, one or more elongated members 800 can couple various layers of the antenna stack assembly 250 together. The elongated members 800 can include a body 802 having a first portion 804 and a second portion 806. The first portion 804 of the body 802 can couple to the lower enclosure 204 such that both the first and second portions 804, 806 of the body 802 extend from the lower enclosure 204 and towards the radome assembly 305. As shown in FIG. 12, the first portion 804 can be wider than the second portion 806, which, in some examples, can form a shoulder 808 at the interface between the first and second portion 804, 806. In some embodiments, the first portion 804 can also be wider than the ports (e.g., the port 331, the port 332, the port 333, the hole 502, and/or the port 381), which allows for one or more layers of the antenna stack assembly 250 to rest against the shoulder 808 of the first portion 804 when the antenna apparatus 200 is assembled. In contrast to the first portion 804, in various embodiments, the second portion 806 can have a width that is less than the width of these ports. As a result of this arrangement, the second portion 806 can extend through the various ports defining the thru-hole 472 of the antenna stack assembly 250.

To couple one or more layers of the antenna stack assembly 250 together, at least a portion of the antenna stack assembly 250 can be placed over one or more elongated members 800 so that at least one layer (e.g., the PCB assembly 380) abuts the shoulders 808 of the elongated members 800. When placed over the elongated members 800, the second portion 806 of the body 802 can extend through the ports of one or more layers of the antenna stack assembly 250. The radome assembly 305 can then be coupled to the elongated members 800 by, for example, welding (e.g., vibration welded, ultrasonic welded, etc.), adhering, or otherwise coupling an end portion 810 of the body 802 to the radome body 402. Coupling the radome assembly 305 to the elongated members 800 can couple the antenna stack assembly 250 together, as the radome body 402 can be joined to elongated members 800 while the remaining layers of the antenna stack assembly 250 are interlocked between the shoulders 808 and the radome body portion 402.

In some embodiments, the elongated members 800 are integrally or monolithically formed with the lower enclosure 204 so that the elongated members 400 and the lower enclosure 204 form a single unitary component. In other embodiments, the elongated members 800 can be formed as separate from the lower enclosure 204 and the radome body assembly 310 and can be later coupled to each of these

components. In various embodiments, the first and second portions **804**, **806** of the elongated members **800** can be formed separately and later coupled together. In other embodiments, the first and second portions **804**, **806** of the elongated members **800** are integrally or monolithically formed.

In various embodiments, the elongated members **400** and/or the elongated members **800** can take the form of a heat stake. In some of these embodiments, or otherwise, the elongated members **400**, **800** can be configured to port thermal energy generated from the antenna assembly to lower enclosure **204** or the radome assembly **305**. For example, the elongated members **400**, **800** can be positioned substantially close to (or can contact) one or more layer of the antenna stack assembly **250**, allowing for at least some of the thermal energy generated by these components to transfer via conduction through the elongated members **400**, **800** and to a separate component of the antenna apparatus **200** (e.g., the outer layer **315**, the lower enclosure **204**, etc.).

In some embodiments, some or all of the layers of the antenna stack assembly **250** may be coupled together using any additional or alternative method. For example, in some embodiments, the end portion **470** may be coupled to the PCB assembly in another manner. For instance, the end portion **470** may be bonded to the PCB layer (and, potentially, additional layers). As another example, a clip may be positioned on the end portion **470** while it is protruding through the port **381** to resist separation of the end portion **470** and the PCB assembly **380**.

In some embodiments, another one or more layers of the antenna stack assembly **250** may include or be coupled to elongated members. For example, the PCB assembly **380** may be formed to have an integrally formed elongated member, or an elongated member may be coupled thereto after formation of the PCB assembly **380**. The elongated member may extend through at least one additional layer and may have an end portion that is reshaped (or bonded, or a clip coupled thereto) while extending through the other one or more layer to resist separation of the one or more layer and the PCB assembly **380**.

In some embodiments, other fasteners may be used to couple two or more layers together in addition to, or instead of, the elongated members. For example, a rivet, bolt, screw, clip, snap-fit connector, or any other fastener may extend through two or more layers of the antenna stack assembly **250** in order to couple the two or more layers together.

In some embodiments, multiple mechanisms may be used to couple the antenna stack assembly **250** together. For example, an elongated member **400** may extend from the radome body assembly **310** through the antenna spacer **335** and be coupled thereto, and rivets may be used to couple the antenna spacer **335** and the PCB assembly **380** together. As another example, a bolt may extend through openings defined by each layer (including the outer layer **315**) and may have a head located outside of one opening (e.g., located above the outer layer **315**) and be coupled to a nut outside of another opening (e.g., located below the PCB assembly **380**) in order to resist separation of each layer relative to the remaining layers. As a further example, one or more elongated members **400** may be used together with one or more elongated members **800** to couple the antenna stack assembly **250** together. In some embodiments, a fastener may be used to couple one or more layer of the antenna stack assembly **250** to the lower enclosure **204** in addition to, or instead of, the method discussed below.

As will be discussed below, the radome body assembly **310** may be disposed within or coupled to the lower enclosure

204 (see, e.g., FIG. 3B). In some examples, the lower enclosure **204** couples to the radome body assembly **310** via the elongated members **800**. Additionally, or alternatively, the lower enclosure **204** may include protrusions **390** (which may have any shape such as triangular prism, pyramid, tube, or the like) which may be located in the volume **258** and may extend upward (e.g., towards the radome body assembly **310**). The protrusions **390** may be sufficiently long so as to contact (and potentially apply pressure to) the PCB assembly **380** in response to coupling between the radome body assembly **310** and the lower enclosure **204**. In that regard, the contact between the protrusions **390**, the PCB assembly **380** (when the lower enclosure **204** is coupled to the radome body assembly **310**), the shoulders **808** of the elongated members **800** (when utilized), and/or the pressure applied through the stack to the radome body assembly **310**, may be sufficient to retain the layers of the antenna stack assembly together without use of adhesives, fasteners, or other coupling means. This contact (and potential pressure) between the protrusions **390**, the PCB assembly **380**, and other components may provide support to one or more layer of the antenna stack assembly **250**.

In some embodiments, multiple coupling mechanisms may be used in some or all locations to provide redundant couplings. For example, the elongated member **400** may be used as shown in FIG. 10, and adhesive may be applied between two or more additional layers (e.g., the upper patch antenna layer **330**, the antenna spacer **335**, and the lower patch antenna layer **370**) to provide redundant coupling. As another example, the outer layer **315**, radome body assembly, upper patch antenna layer **330**, and antenna spacer **335** may be coupled together using a first fastener; the antenna spacer **335**, the lower patch antenna layer **370**, the dielectric layer **375**, and the PCB assembly **380** may be coupled together using a second fastener; and adhesive may be used to couple the lower patch antenna layer **370** to the dielectric layer **375**.

In some embodiments, the elongated member **400** may be formed from a same material as the remainder of the radome body assembly **310**. In some embodiments, the elongated member **400** may be strengthened, for example by using a coating, to increase its strength. In some embodiments, the elongated member **400** may be formed separate from the radome body assembly **310** and coupled to the radome body assembly **310** using any means (e.g., fasteners, adhesives, chemical bonding, or the like). In these embodiments, the elongated member **400** may be formed from the same or different material as the remainder of the radome body assembly **310**. Similarly, any additional fasteners, connectors, or the like discussed herein may be formed from any material such as a polymer, a metal, or the like.

Coupling of Antenna Assembly

Turning to FIGS. 2A, 3B, and 11, the antenna stack assembly **250** may be coupled to the housing assembly **202**, which includes a radome portion **206** and a lower enclosure **204**, to assemble the antenna apparatus **200** together. As discussed above, in some embodiments, the antenna stack assembly **250** may be coupled together first and then the antenna stack assembly **250** may be coupled to either the radome portion **206** or the lower enclosure **204**. As will be discussed in more detail below, in various examples, the antenna stack assembly **250** may be coupled together and to the housing assembly **202** within the same coupling process. Stated differently, in various examples, coupling the radome body assembly **310** and the housing assembly **202** together may also couple the layers of the antenna stack assembly **250** together.

The radome body assembly **310** may include a perimeter portion **700** which may be located at the exterior portion **328** of the radome body portion **402**. The perimeter portion **700** may extend outward from (e.g., in a direction perpendicular to the stacking axis) some or all remaining layers of the antenna stack assembly **250** (e.g., may at least extend outward from the upper patch antenna layer **330**, the antenna spacer **335**, the lower patch antenna layer **370**, the dielectric layer **375**, and the PCB assembly **380**). The perimeter portion **700** may extend outward from these layers around the entire perimeter of the radome body assembly **310**. In some embodiments, the perimeter portion **700** may be an extension of the radome body portion **402**. In some embodiments, the perimeter portion **700** may be an extension of the radome spacer portion **404**. In some embodiments, the perimeter portion **700** may be an extension of at least a portion of both of the radome body portion **402** and the radome spacer portion **404**. In some embodiments, the perimeter portion may fail to be aligned with one or both of the radome body portion **402** and the radome spacer portion **404**.

In some embodiments, the outer layer **315** may extend to an outer edge of the perimeter portion **700**. In some embodiments, the outer layer **315** may fail to extend onto the perimeter portion **700**. In some embodiments, the outer layer **315** may extend a portion of the way onto the perimeter portion **700** but may end before the outer edge of the perimeter portion **700**. The outer layer **315** may be pre-cut to fit as desired or may be applied to the radome body assembly **310** and then cut to a desired shape.

The perimeter portion **700** may include a parallel portion **701** that extends in a direction substantially parallel to the plane defined by the radome body portion **402**. The perimeter portion **700** may further include a radome lip **704** that extends away from the parallel portion **701** and at least partially downward (e.g., towards the lower enclosure **204**). In some embodiments, the radome lip **704** may form an angle with the parallel portion **701** that is between 45 degrees and 135 degrees, between 60 degrees and 120 degrees, between 75 degrees and 105 degrees, or about 90 degrees. The transition from the parallel portion **701** to the radome lip **704** may be angled, curved, or any combination thereof.

The parallel portion **701** of the perimeter portion **700** may have an inner surface (e.g., facing towards the lower enclosure **204**) that extends from, for example, the radome spacer portion **404** to the radome lip **704**. The inner surface may include a bonding or joining surface **702** used to couple the radome body assembly **310** to the lower enclosure **204**. As described herein, the terms bonding and joining may be used interchangeably to describe welding (whether by heat, ultrasonic, or vibration welding techniques, adhesive coupling, or other joining methods).

The lower enclosure **204** may also have a perimeter portion **710**. The perimeter portion **710** of the lower enclosure **204** may extend around an entire perimeter of the lower enclosure **204**. As shown, the lower enclosure **204** may be angled or slanted towards the perimeter portion **710** between the perimeter portion **710** and the interface between the post **210** and the lower enclosure **204**. In some embodiments, the slant may only exist for a portion of the lower enclosure **204**, may fail to exist, may exist along the entire lower enclosure **204**, or the like. Similarly, the lower enclosure **204** may be curved instead of angled, may include a combination of angles and curves, or the like. This angled or slanted design of the lower enclosure aids in forming the volume **258** between the lower enclosure **204** and the PCB assembly **380**.

However, any other shape may be used for the lower enclosure **204** without departing from the scope of the present disclosure.

The perimeter portion **710** of the lower enclosure **204** may include a post **712** extending away therefrom in an upwards direction (e.g., towards the radome body assembly **310**). For example, the post **712** may extend in a direction that is substantially perpendicular to the plane defined by the radome body portion **402**. The post **712** may include an upper surface or edge which may be used as a joining or bonding edge **714**. The bonding edge **714** may include a surface or edge that is substantially parallel to the bonding surface **702** of the perimeter portion **700** of the radome body assembly **310**. The perimeter portion **710** of the lower enclosure **204** may also include an enclosure lip **716** extending substantially parallel to (e.g., within 45 degrees of parallel, within 30 degrees, within 20 degrees, within 5 degrees, or the like) the radome lip **704**, and may likewise extend substantially parallel to (e.g., within 45 degrees of parallel, within 30 degrees, within 20 degrees, within 5 degrees, or the like) the post **712**. In some embodiments, the enclosure lip **716** may be spaced from the post **712** by a distance. In some embodiments, one or both of the radome lip **704** and the enclosure lip **716** may be optional.

The bonding edge **714** of the post **712** may be coupled to the bonding surface **702** of the parallel portion **701** of the radome body assembly **310**. Because the bonding surface **702** and the bonding edge **714** extend around the entire perimeters of the radome body assembly **310** and the lower enclosure **204**, the entire perimeters of the radome body assembly **310** and the lower enclosure **204** may be coupled together. This coupling between the bonding surface **702** and the bonding edge **714** may partially or entirely seal the volume **258** from an environment of the antenna assembly **200**. Likewise, this coupling may be waterproof or water resistant (e.g., the radome body assembly **310** may be hermetically sealed to the lower enclosure **204**). Thus, the coupling of the radome body assembly **310** to the lower enclosure **204** may reduce the likelihood of water or debris entering the volume **250**. Thus, components within the volume (including the entire antenna stack **250** minus portions of the radome assembly **305**) may be protected from water and debris that may be present in the environment of the antenna assembly **200**.

The bonding surface **702** may be coupled to the bonding edge **714** in any manner. In some embodiments, an O-ring or other sealing member may be present between the bonding surface **702** and the bonding edge **714** and a fastener may be used to fasten the lower enclosure **204** to the radome body assembly **310** such that the O-ring or other sealing member hermetically seals the volume **258** from the environment. In some embodiments, an adhesive may be placed between the bonding surface **702** and the bonding edge **714** and cured to couple the bonding surface **702** and the bonding edge **714** together. In some embodiments, the bonding surface **702** and the bonding edge **714** may be chemically bonded together.

In some embodiments, vibration welding may be used to couple the bonding surface **702** and the bonding edge **714** together. Vibration welding refers to a process in which two workpieces (the radome body assembly **310** and the lower enclosure **204**) are brought into contact under pressure, and a reciprocating motion (e.g., vibration) is applied along the common interface (the bonding surface **702** and the bonding edge **714**) to generate heat. The resulting heat melts the workpieces, and they become welded when the vibration stops and the interface cools. The vibration may be achieved either through linear vibration welding, which uses a one-

dimensional back-and-forth motion, or orbital vibration welding which moves the pieces in small orbits relative to each other. The vibrations may operate at a frequency between 120 hertz and 360 hertz, between 200 hertz and 280 hertz, between 220 hertz and 260 hertz, about 240 hertz, or the like. The amplitude of the vibration may be, for example, between 20 mil and 118 mil (0.5 mm and 3 mm), between 40 mil and 78 mil (1 mm and 2 mm), or about 59 mil (1.5 mm).

The vibration weld between the bonding surface 702 and the bonding edge 714 may result in a hermetic seal formed around the entire bonding surface 702 and the entire bonding edge 714. Vibration welding may be optimally performed using thermoplastics. In that regard and in some embodiments, the radome body assembly 310 and the lower enclosure 204 may include a thermoplastic (at least at the respective perimeter portions 700, 710). In some embodiments, one or both of the radome body assembly 310 and the lower enclosure 204 may include a different material. For example, the radome body assembly 310 may include a thermoplastic and the lower enclosure 204 may include a non-thermoplastic polymer or a metal. In some embodiments, both the radome body assembly 310 and the lower enclosure 204 may include a non-thermoplastic polymer or a metal.

In some embodiments, a different bonding technique may be used. For example, ultrasonic welding may be used to bond two thermoplastics, a thermoplastic and a metal, two metals, or the like together. Ultrasonic welding is a process in which high-frequency (e.g., between 20 kilohertz and 40 kilohertz) ultrasonic acoustic vibrations are locally applied to workpieces (e.g., the radome body assembly 310 and the lower enclosure 204) being held together under pressure to create a solid-state weld. Ultrasonic welding may be particularly useful when the two workpieces are formed using dissimilar materials (e.g., a polymer for one and a metal for the other).

After the vibration welding, ultrasonic welding, or other coupling technique is completed, a joint 720 may be present between the bonding surface 702 and the bonding edge 714. The joint 720 may also operate as a hermetic seal, sealing the volume 258 from the environment of the antenna assembly 200.

After the bonding surface 702 and the bonding edge 714 have been bonded together (e.g., using vibration welding, ultrasonic welding, or any other coupling technique), a gap 722 may be present between the radome lip 704 and the enclosure lip 716. In some embodiments and due to variation present in various welding applications, the joint 720 between the post 712 and the bonding surface 702 may be sufficiently large (e.g., by melting a sufficiently large portion of the post 712 so as to reduce its height along the stacking axis) to cause the gap 722 to be nonexistent. However, in some embodiments, the joint 720 may not remove this quantity of material from the post 712. In that regard, the presence of the gap 722 between the radome lip 704 and the enclosure lip 716 may provide the appearance of a close seal between the radome body assembly 310 and the lower enclosure 204 while providing for the variation in welding applications. Although the gap 722 may be present between the radome lip 704 and the enclosure lip 716 such that water and debris may pass through the gap 722, the seal between the bonding surface 702 and the bonding edge 714 of the post is sufficient to resist entry of this water or debris into the volume 258 in which sensitive electronic components may be located.

As mentioned above with reference to the embodiment of FIG. 12, the radome body assembly 310 can be coupled to

the elongated members 800 by, for example, welding (e.g., vibration welded, ultrasonic welded, etc.), adhering, or otherwise coupling an end portion 810 of the body 802 to the radome body 402. In some embodiments, the post 712 may be coupled to the radome body assembly 310 during the same coupling process as the elongated member 800 is coupled to the radome body assembly 310. For example, the post 712 can be ultrasonic welded to the radome body assembly 310 at the same time (or at the same step or process) as the elongated member 800 is ultrasonic welded to the radome body assembly 310. The sites of joining of the elongated members 800 to the radome assembly 305 may be in the same plane as the sites of joining of the lower enclosure 204 and the radome body assembly 310 to facilitate such welding (or other joining methods). Stated differently, the ends of the posts 712 and the elongated members 800 may be substantially equidistant from radome body portion 402. By arranging the posts 712 and the elongated members 800 in this manner, a uniform force can be applied to the radome body assembly 310 when coupling the radome body assembly 310 to the posts 712 and the elongated members 800 to assist with coupling the components together. The post 712 and the elongated member 800 can be coupled to the radome body assembly 310 using any various coupling method described herein, including, for instance, vibration welding and bonding.

Although a variety of examples and other information was used to explain aspects within the scope of the appended claims, no limitation of the claims should be implied based on particular features or arrangements in such examples, as one of ordinary skill would be able to use these examples to derive a wide variety of implementations. Further and although some subject matter may have been described in language specific to examples of structural features and/or method steps, it is to be understood that the subject matter defined in the appended claims is not necessarily limited to these described features or acts. For example, such functionality can be distributed differently or performed in components other than those identified herein. Rather, the described features and steps are disclosed as examples of components of systems and methods within the scope of the appended claims.

Claim language and language within the specification reciting "at least one of" refers to at least one of a set and indicates that one member of the set or multiple members of the set satisfy the claim. For example, claim language and language within the specification reciting "at least one of A and B" means A, B, or A and B. As another example, claim language and language within the specification reciting "at least one of A or B" means A, B, or A and B.

We claim:

1. A radome assembly for use with an antenna assembly, the radome assembly comprising:
 - a radome body portion having a first surface and a second surface, wherein the second surface is opposite the first surface, and wherein the radome body portion defines a portion of a housing for an antenna assembly; and
 - a radome spacer portion extending from the second surface of the radome body portion, the radome spacer portion defining a plurality of cells that are formed from a plurality of cell walls, wherein at least two cell walls of the plurality of cell walls defining each cell of the plurality of cells are positioned adjacent to each other and define a gap therebetween, and wherein each cell wall includes a first end coupled to the second surface and a second end coupled to the antenna

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- assembly, each cell wall having a spacing height between the first and second ends.
2. The radome assembly of claim 1, wherein the radome body portion and the radome spacer portion are formed using a first material.
3. The radome assembly of claim 2, wherein the first material includes a polymer.
4. The radome assembly of claim 3, wherein the polymer includes at least one of polypropylene (PP), polycarbonates, polybutylene terephthalate (PBT), polyphenylene ether (PPE), poly(p-phenylene oxide) (PPO), polystyrene (PS), polyethylene terephthalate (PET), polyvinyl chloride (PVC), and liquid crystal polymer (LCP).
5. The radome assembly of claim 1, wherein the radome body portion and the radome spacer portion are formed using the same material.
6. The radome assembly of claim 1, wherein each of the cell walls that define a first cell also functions as a cell wall of at least another cell of the plurality of cells.
7. The radome assembly of claim 1, wherein each of the plurality of cells is defined by 6 cell walls.
8. The radome assembly of claim 1, wherein a vertical pathway of each of the plurality of cells is configured to be aligned with a respective antenna element of the antenna assembly.

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9. The radome assembly of claim 1, wherein the first surface is a planar surface.
10. The radome assembly of claim 1, wherein the radome body portion and the radome spacer portion are integrally formed.
11. The radome assembly of claim 1, wherein the plurality of cells are nodeless cells.
12. The radome assembly of claim 1, wherein the radome assembly has a thickness of greater than or equal to 3 mm.
13. The radome assembly of claim 1, further comprising a hydrophobic outer layer coupled to the first surface of the radome body portion.
14. The radome assembly of claim 13, wherein the radome body portion and the radome spacer portion are formed from a first material and the hydrophobic outer layer is formed by a second material.
15. The radome assembly of claim 14, wherein the adhesive is a pressure sensitive adhesive (PSA).
16. The radome assembly of claim 13, wherein the outer layer is coupled to the first surface of the radome body portion using an adhesive.
17. The radome assembly of claim 1, wherein the outer layer has a thickness that is less than or equal to 60 thousandths of an inch.

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